Chapter 7

DC-DC Switch-Mode Converters

Chapter 7 dc–dc Switch-Mode Converters **161**

- dc-dc converters for switch-mode dc power supplies and dc-motor drives

Block Diagram of DC-DC Converters

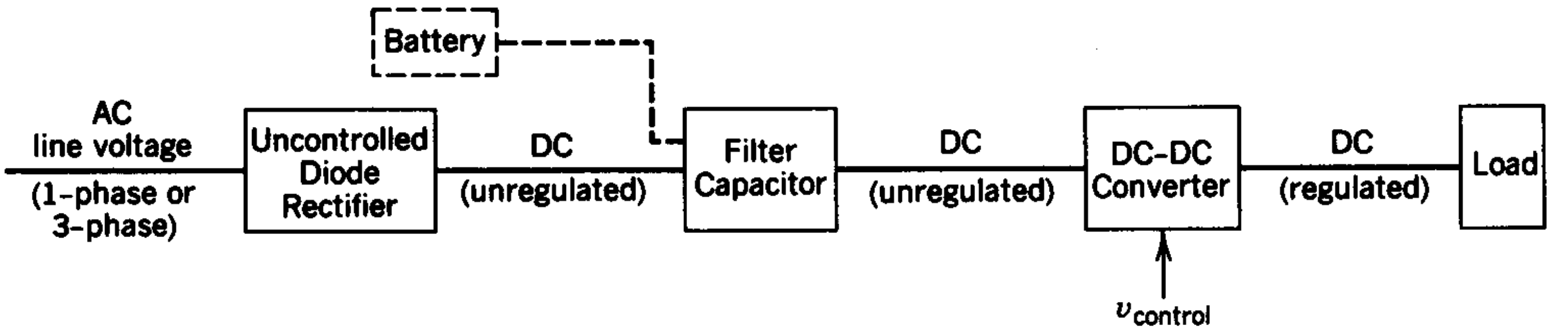


Figure 7-1 A dc–dc converter system.

- Functional block diagram

Stepping Down a DC Voltage

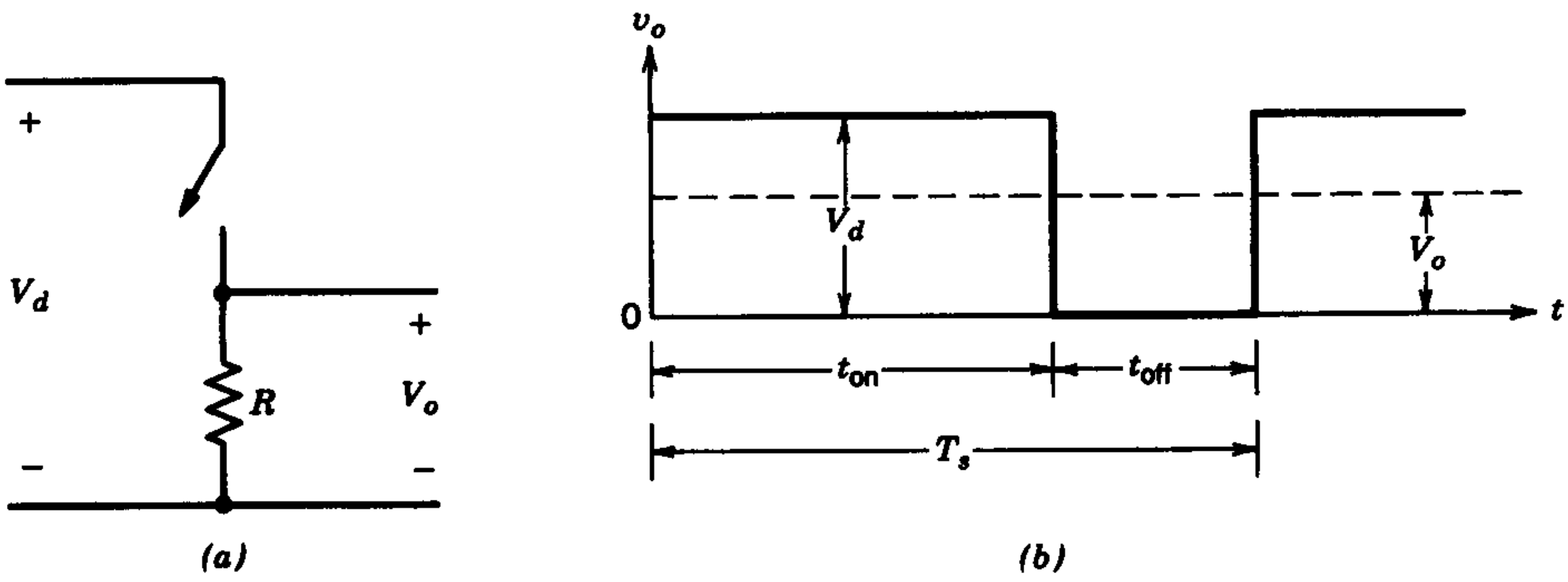


Figure 7-2 Switch-mode dc–dc conversion.

- A simple approach that shows the evolution

Pulse-Width Modulation in DC-DC Converters

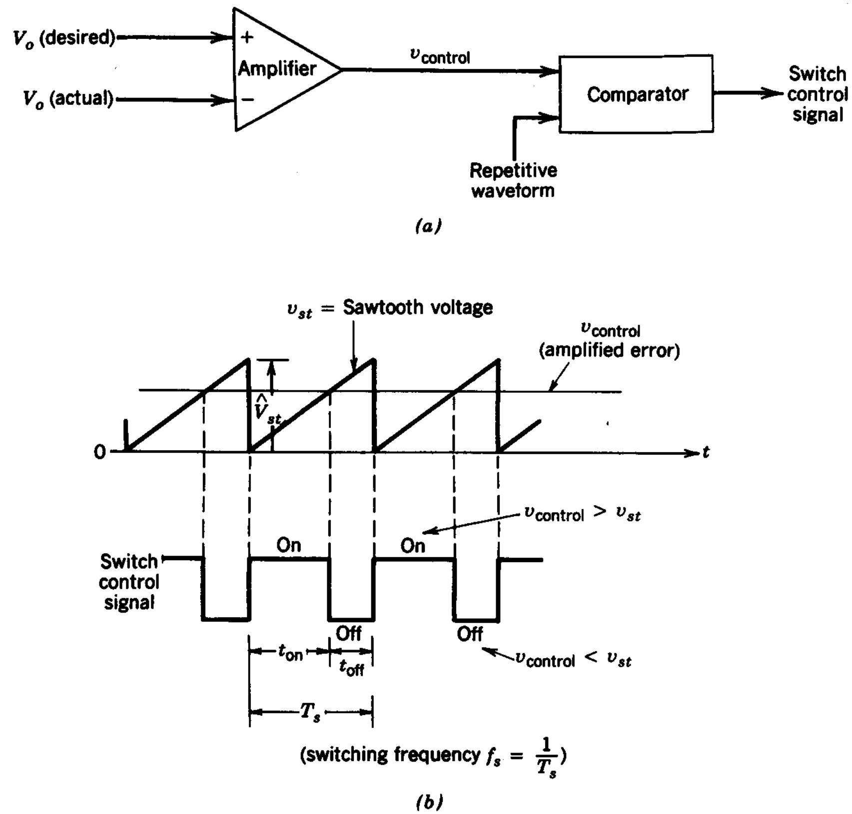


Figure 7-3 Pulse-width modulator: (*a*) block diagram; (*b*) comparator signals.

- Role of PWM

Duty cycle

- Switching frequency given by the sawtooth
- Control voltage u_{control} is the diffence between reference and measured voltages amplified by the controller
  - u_{control} gives the on-time of the switch t_{on}
- Relative on time, duty cycle

$$D = \frac{t_{on}}{T_s} = \frac{u_{ohj}}{\hat{U}_{st}}$$

Step-Down DC-DC Converter

- Pulsating input to the low-pass filter
- The larger the difference between the corner frequency of the filter *f*c and switching frequency *f*s the better filtering is

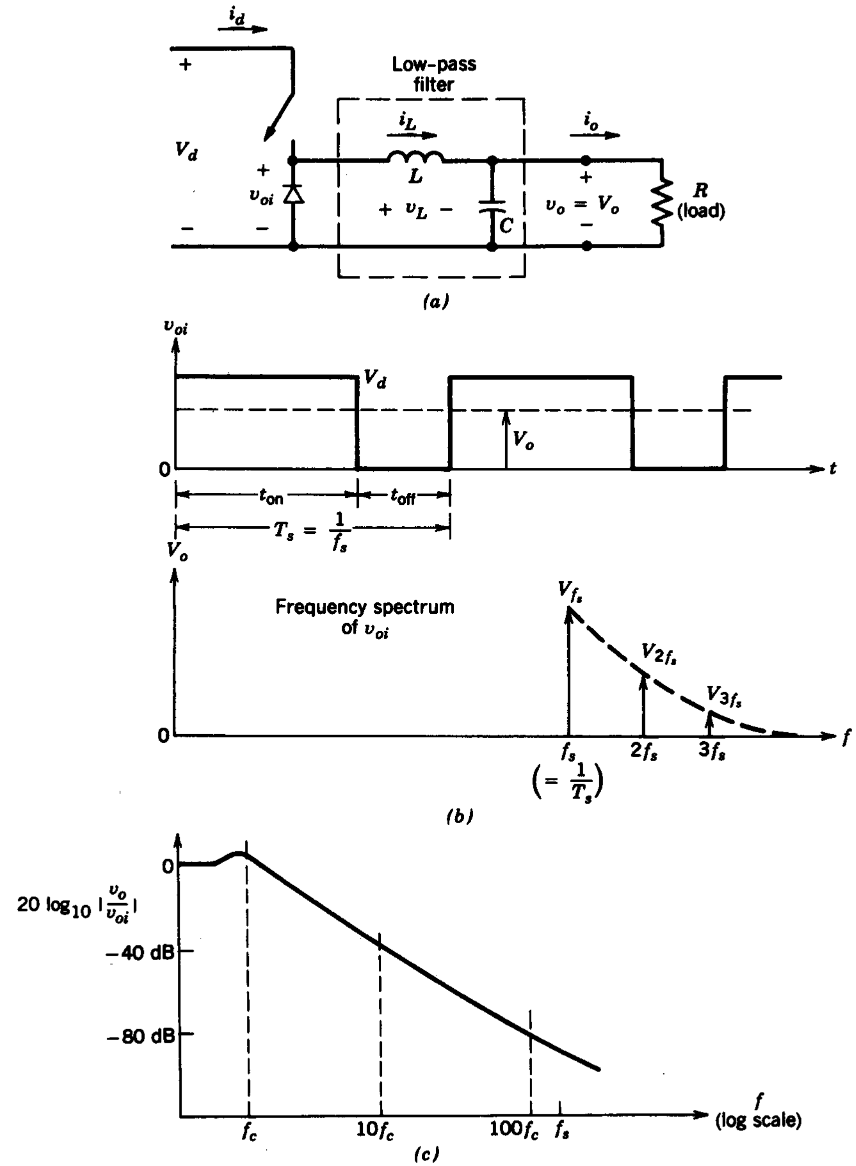


Figure 7-4 Step-down dc–dc converter.

Output voltage

- In continuous conduction mode (CCM)

$$V_o = \frac{1}{T_s}\int_0^{T_s} v_o(t)\,dt = \frac{t_{on}}{T_s} V_d = D V_d$$

- Output depends linearly from the
  - Duty cycle
  - and therefore also from control voltage $u_{control}$
- Discontinuous conduction mode (DCM)
  - Will be discussed in next slides
  - Also output current (power) has an effect on voltage average
  - Nonlinear dependence on the duty cycle

Step-Down DC-DC Converter: Waveforms

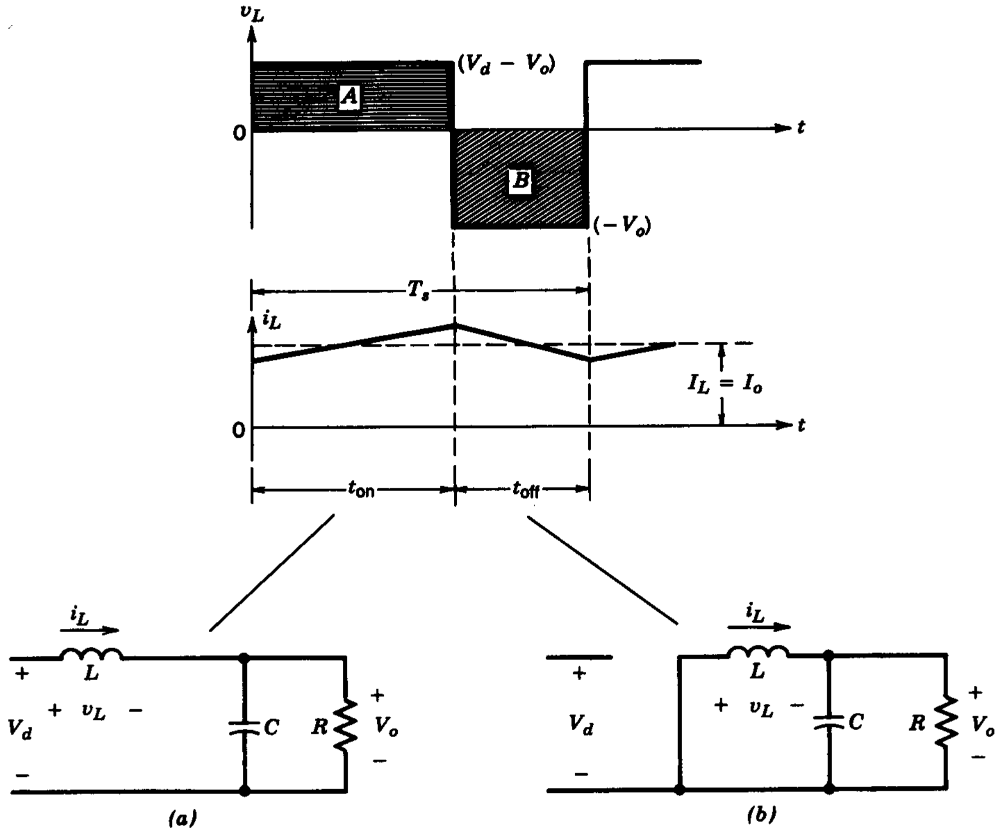


Figure 7-5 Step-down converter circuit states (assuming i_L flows continuously): (*a*) switch on; (*b*) switch off.

- Steady state; inductor current flows continuously

Continuous Conduction Mode, CCM

- Voltage integral over the inductor must be zero at steady state

$$(V_d - V_o)\, t_{on} = V_o\,(T_s - t_{on})$$

$$\Rightarrow \frac{V_o}{V_d} = \frac{t_{on}}{T_s} = D$$

- If there are no losses in the converter

$$V_d I_d = V_o I_o \qquad \Rightarrow \frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1}{D}$$

”Transformer”

- In CCM operates like transformer without galvanic isolation
  - Duty cycle D acts like a portabless turns ratio in a transformer, changes from 0 to 1
- Input current i_d changes also as the switch operates
  - In many cases filtering needed in the input side too, depends on the supplying voltage source

Filtering

- Filter inductance ensures that output is current source as input normally is voltage source
- Filter corner frequency f_C
  - *Selected to be much smaller than f_s*
  - Attenuation of harmonics is high
  - Output voltage can be assumed to be constant in many cases

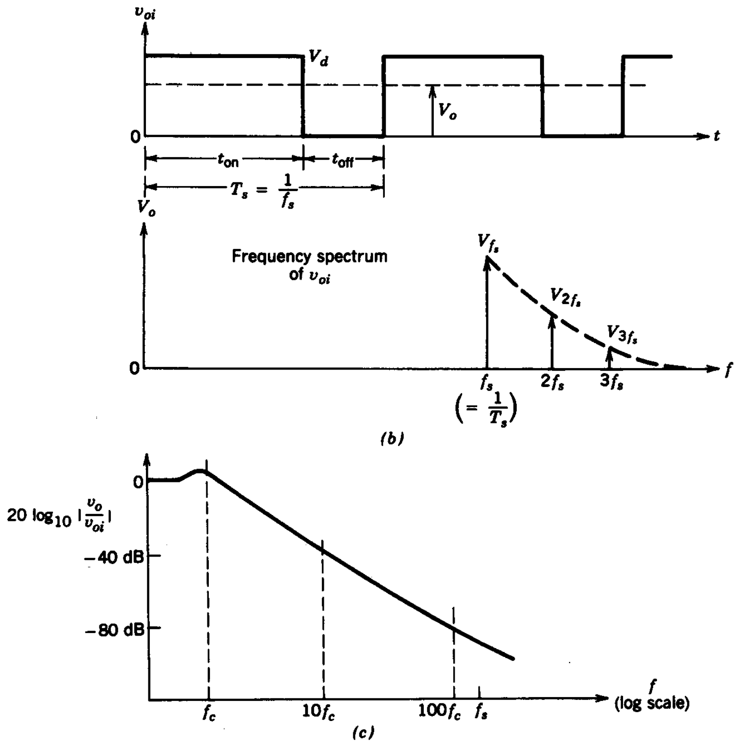


Figure 7-4 Step-down dc–dc converter.

Step-Down DC-DC Converter: Waveforms at the boundary of Cont./Discont. Conduction

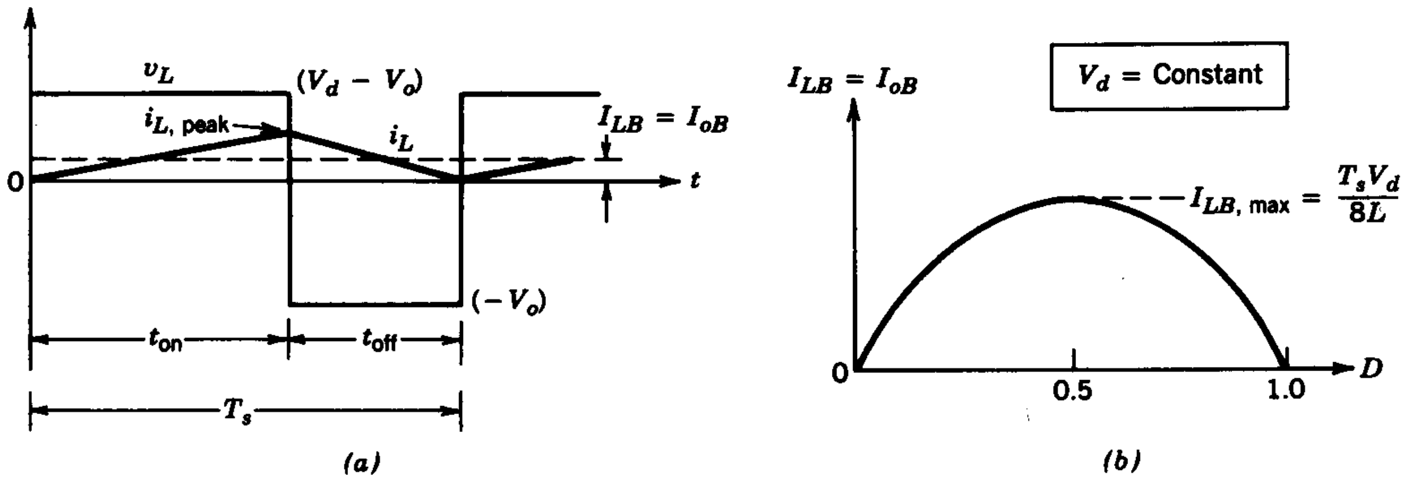


Figure 7-6 Current at the boundary of continuous–discontinuous conduction: (*a*) current waveform; (*b*) I_{LB} versus D keeping V_d constant.

- Critical current below which inductor current becomes discontinuous

$$I_{LB} = \frac{i_{Lpeak}}{2} = \frac{U_d - U_o}{2L} t_{on} = \frac{DT_s}{2L}(U_d - U_o) = I_{oB}$$

Step-Down DC-DC Converter: Discontinuous Conduction Mode

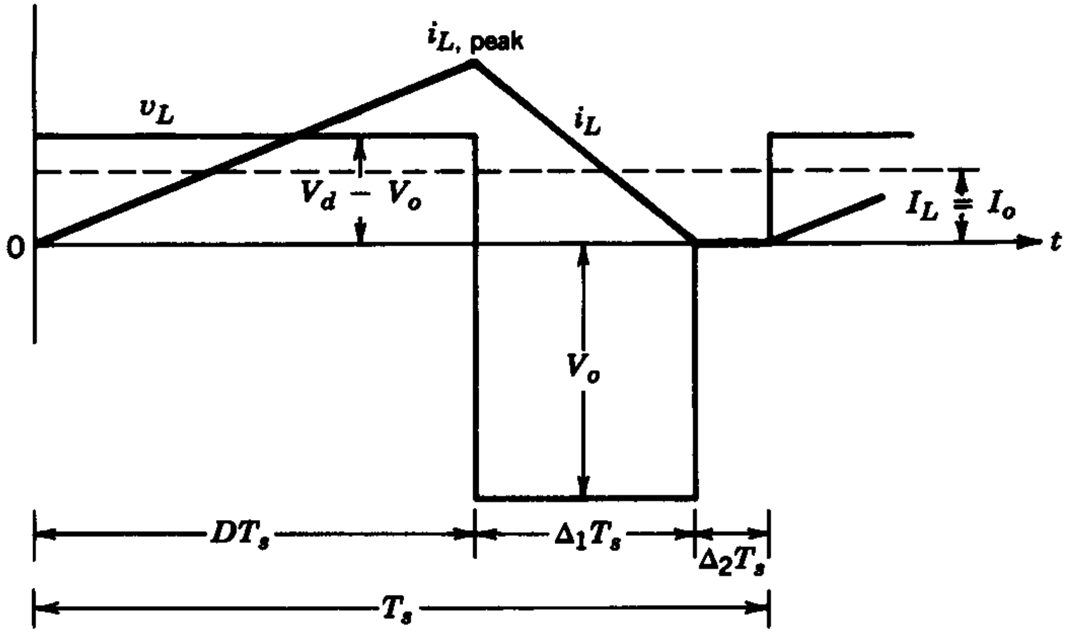


Figure 7-7 Discontinuous conduction in step-down converter.

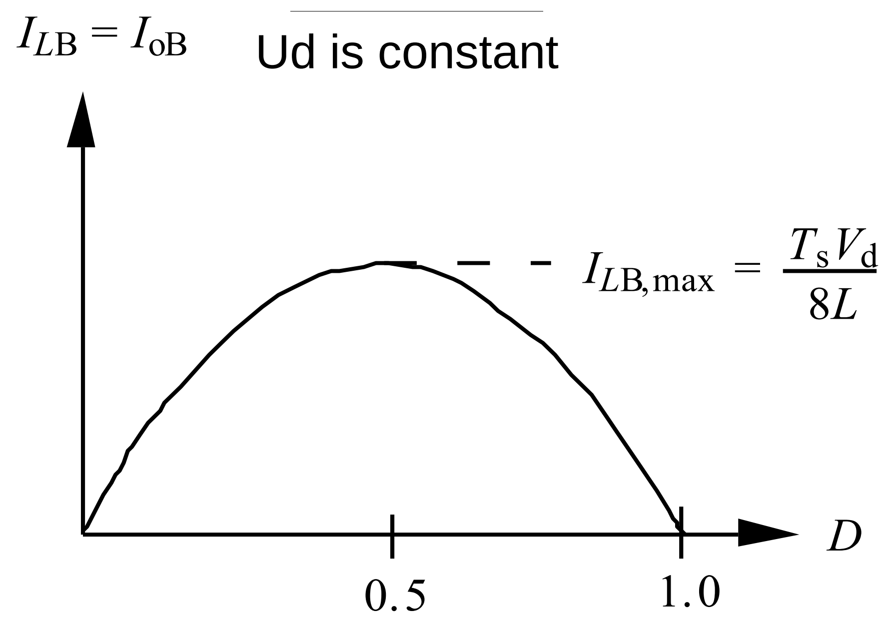
- Steady state; inductor current discontinuous

DCM with constant Ud

- Typical in motor drives
- Replacing $U_o = DU_d$ we end up to

$$I_{LB} = \frac{DU_d T_s}{2L}(1-D) = I_{oB}$$

- Highest output current for CCM needed at D = 0,5



U_o/U_d in DCM with constant Ud

- Voltage integral over the inductor

$$(U_d - U_o) DT_s - U_o \Delta_1 T_s = 0 \quad \Rightarrow \quad \frac{U_o}{U_d} = \frac{D}{D + \Delta_1}$$

- Average of output current

$$I_o = i_{Lpeak} \frac{D + \Delta_1}{2} = \frac{U_o}{L} \Delta_1 T_s \frac{D + \Delta_1}{2} = \frac{U_d T_s}{2L} D \Delta_1$$

$$\Rightarrow \Delta_1 = \frac{1}{4} \frac{I_o}{I_{LB\max} D}$$

- Replacing we obtain

$$\frac{U_o}{U_d} = \frac{D^2}{D^2 + \frac{1}{4} \frac{I_o}{I_{LB\max}}}$$

Step-Down DC-DC Converter: Limits of Cont./Discont. Conduction

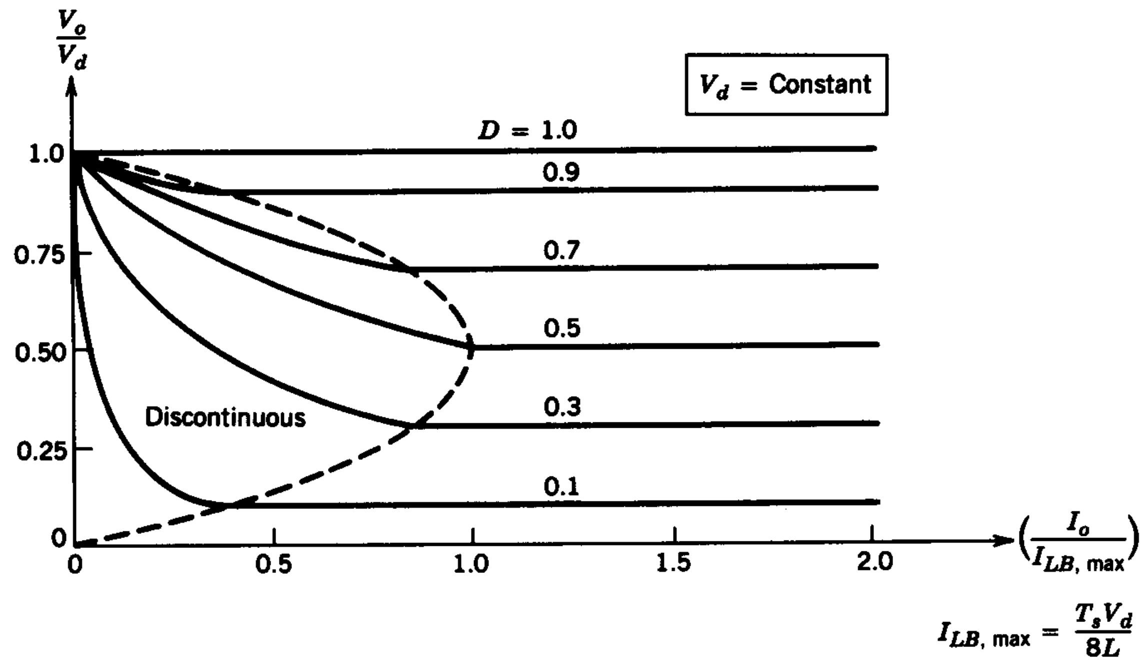


Figure 7-8 Step-down converter characteristics keeping V_d constant.

• The duty-ratio of 0.5 has the highest value of the critical current

DCM with constant U_o

- Typical in power supplies
- Replacing $U_d = U_o / D$

$$I_{LB} = \frac{i_{Lpeak}}{2} = \frac{U_d - U_o}{2L} t_{on} = \frac{T_s U_o}{2L}(1 - D)$$

- Maximum required current for CCM when $D = 0$

$$I_{LB\max} = \frac{T_s U_o}{2L}$$

Duty cycle in DCM with constant U_o

- Using previous equations

$$\frac{U_o}{U_d}=\frac{D}{D+\Delta_1}=\frac{D}{D+\dfrac{2LI_o}{U_d D T_s}}=\frac{D}{D+\dfrac{U_o}{U_d D}\dfrac{I_o}{I_{LB\max}}}\Leftrightarrow\frac{U_o}{U_d}\left(D^2+\frac{U_o}{U_d}\frac{I_o}{I_{LB\max}}\right)=D^2$$

- Duty cycle is

$$D=\frac{U_o}{U_d}\sqrt{\frac{I_o/I_{LB\max}}{1-U_o/U_d}}$$

- Ratio of voltages is nonlinear

$$\frac{U_o}{U_d}=\frac{-D^2+D\sqrt{D^2+4I_o/I_{LB\max}}}{2I_o/I_{LB\max}}$$

Step-Down DC-DC Converter: Limits of Cont./Discont. Conduction

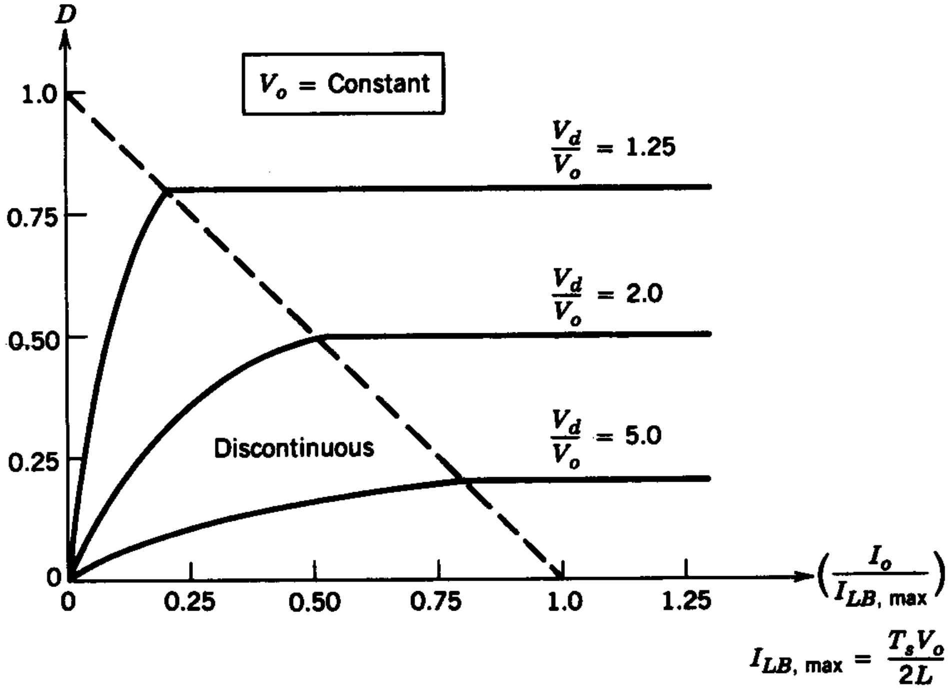


Figure 7-9 Step-down converter characteristics keeping V_o constant.

- Output voltage is kept constant

Step-Down Conv.: Output Voltage Ripple

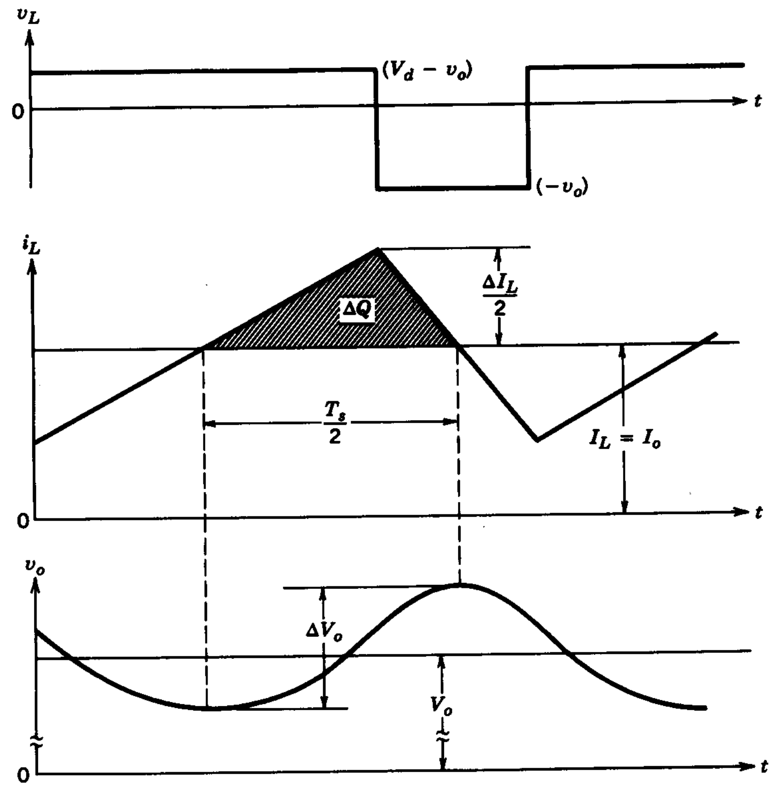


Figure 7-10 Output voltage ripple in a step-down converter.

- ESR is assumed to be zero

Ripple (sykkeisyys in Finnish)

- Peak-to-peak

$$\Delta U_o = \frac{\Delta Q}{C} = \frac{1}{2C}\frac{\Delta I_L}{2}\frac{T_s}{2} \qquad \Delta I_L = \frac{U_o}{L}t_{off} = \frac{U_o}{L}\left(T_s - t_{on}\right) = \frac{U_o}{L}\left(1-D\right)T_s$$

$$\frac{\Delta U_o}{U_o} = \frac{1}{8}\frac{T_s^2}{LC}\left(1-D\right) = \frac{\pi^2}{2}\left(1-D\right)\left(\frac{f_c}{f_s}\right)^2 \quad \text{jossa } f_c = \frac{1}{2\pi\sqrt{LC}}$$

- Ripple reduces when $f_C \ll f_s$
  - Compare to Fig 7-4
- In CCM doesn't depend on output power
- Allowed ripple often < 1 %
  - $u_o(t) = U_o$ can be assumed to be constant

Step-Up DC-DC Converter (Boost)

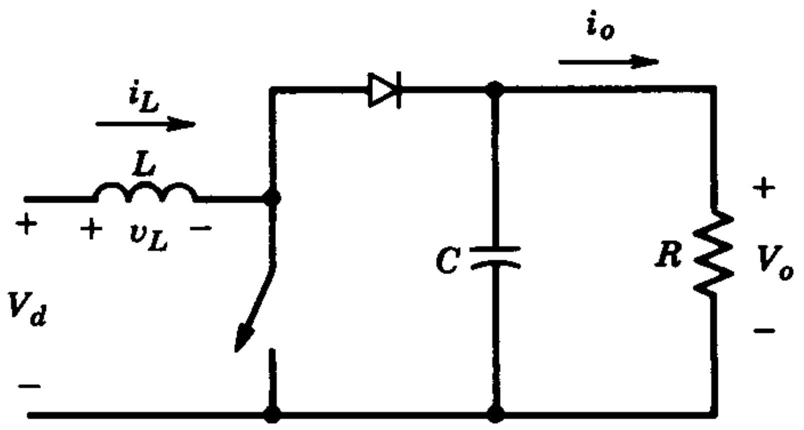


Figure 7-11 Step-up dc–dc converter.

- Output voltage must be greater than the input

Step-Up DC-DC Converter Waveforms

$$U_d t_{on} + (U_d - U_o) t_{off} = 0 \quad \Leftrightarrow \quad \frac{U_o}{U_d} = \frac{T_s}{t_{off}} = \frac{1}{1-D}$$

$$U_d I_d = U_o I_o \quad \Leftrightarrow \quad \frac{I_o}{I_d} = \frac{U_d}{U_o} = 1 - D$$

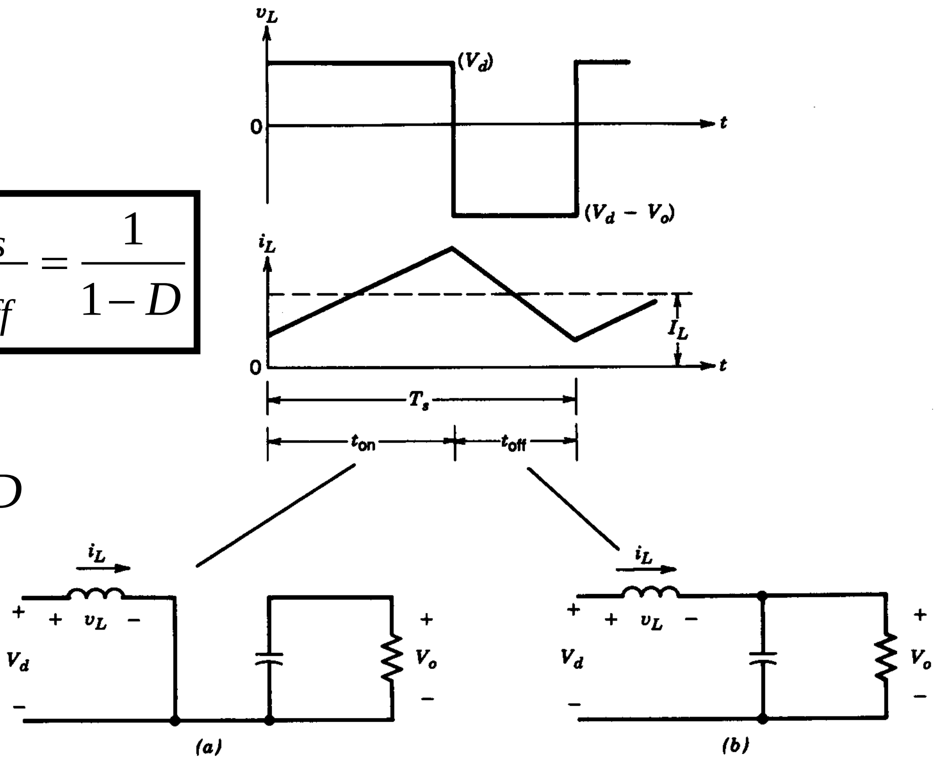


Figure 7-12 Continuous-conduction mode: (*a*) switch on; (*b*) switch off.

- Continuous current conduction mode

Step-Up DC-DC Converter: Limits of Cont./Discont. Conduction, constant Uo

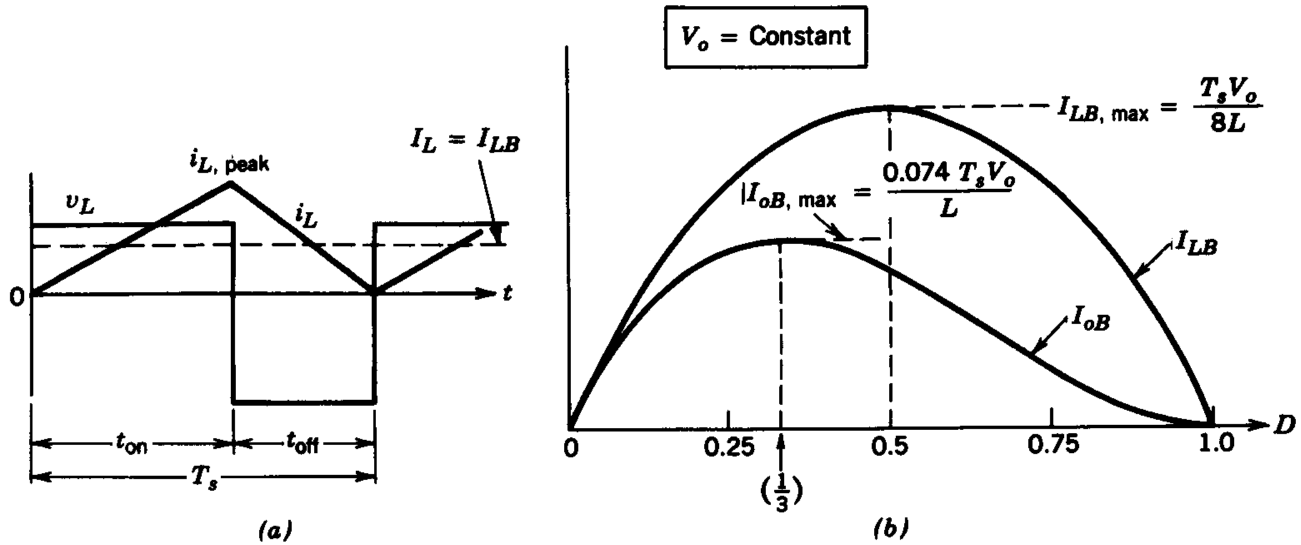


Figure 7-13 Step-up dc–dc converter at the boundary of continuous–discontinuous conduction.

$$I_{LB} = \frac{i_{Lpeak}}{2} = \frac{U_d}{2L} t_{on} = \frac{T_s U_o}{2L} D(1-D)$$

$$I_{oB} = I_{LB}(1-D) = \frac{T_s U_o}{2L} D(1-D)^2$$

$$I_{oB\max} = \frac{2}{27} \frac{T_s U_o}{L}$$

- Note $I_L \neq I_o$

Step-Up DC-DC Converter: DCM, constant Uo

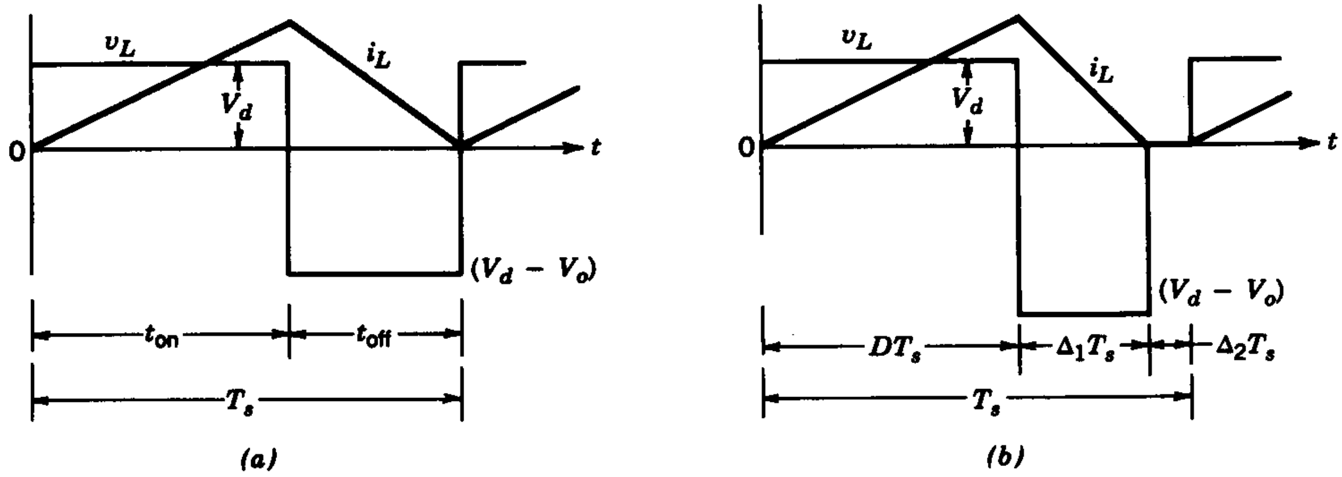


Figure 7-14 Step-up converter waveforms: (*a*) at the boundary of continuous–discontinuous conduction; (*b*) at discontinuous conduction.

$$U_d DT_s + (U_d - U_o)\Delta_1 T_s = 0 \quad \Leftrightarrow \quad \frac{U_o}{U_d} = \frac{D+\Delta_1}{\Delta_1} \qquad \frac{I_o}{I_d} = \frac{\Delta_1}{D+\Delta_1}$$

$$I_d = \frac{U_d}{2L} DT_s \frac{D+\Delta_1}{1} \quad \text{and} \quad I_o = \frac{T_s U_d}{2L} D\Delta_1 \qquad D = \frac{U_o}{U_d}\Delta_1 - \Delta_1 = \sqrt{\frac{4}{27}\frac{U_o}{U_d}\left(\frac{U_o}{U_d} - 1\right)\frac{I_o}{I_{oB\max}}}$$

Step-Up DC-DC Converter: Limits of Cont./Discont. Conduction

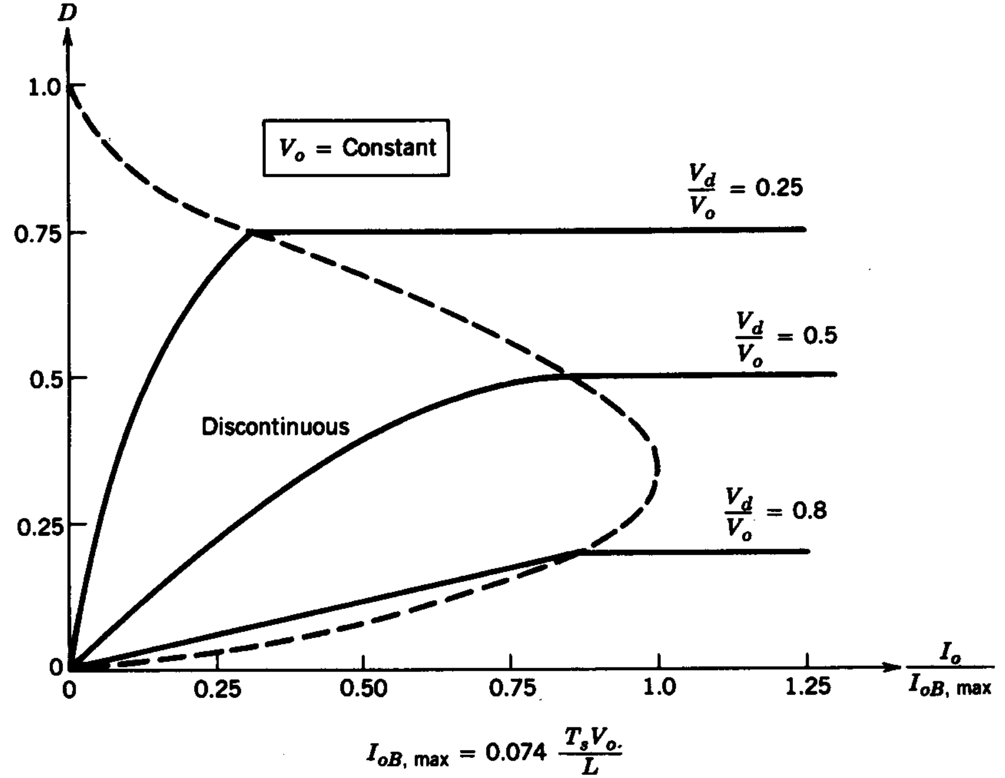


Figure 7-15 Step-up converter characteristics keeping V_o constant.

- The output voltage is held constant

Step-Up DC-DC Converter: Effect of Parasitics

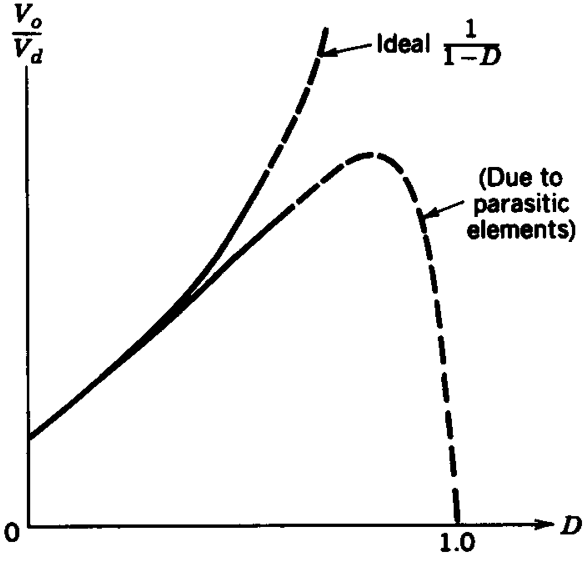


Figure 7-16 Effect of parasitic elements on voltage conversion ratio (step-up converter).

- The duty-ratio is generally limited before the parasitic effects become significant

Effect of Parasitics

- Especially nonidealities, i.e. resistive losses in L and C
- At large D, peak value of current is large when compared to the average value
  - Major part of input voltage is needed to overcome the voltage drop of parasitics
  - Losses are increasing too
  - Output voltage ripple and capacitor current increase too

Effect of Parasitics, U_o/U_d

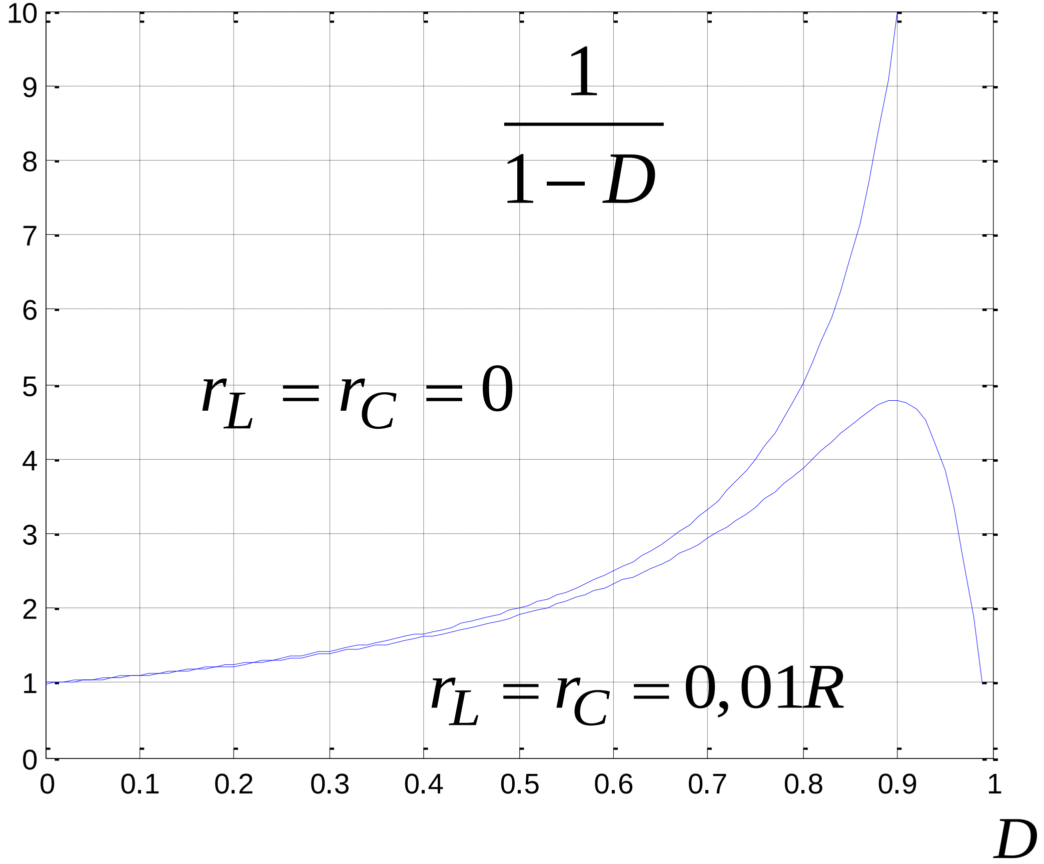
- Losses of inductor and capacitor, r_L , r_c
  - Resistors are percentages of load resistor *R*
- It can be shown that

$$\frac{U_o}{U_d} = \frac{1}{1-D}\frac{(1-D)^2 R}{R'}$$ where $$R' = r_L + \frac{Rr_C}{R+r_C}(1-D) + \frac{R^2(1-D)^2}{R+r_C}$$

- Analysis of transfer functions in Chapter 10 gives this

U_o/U_d when parasitics are 1 %

$$\frac{U_o}{U_d}$$



Effect of Parasitics, U_o/U_d

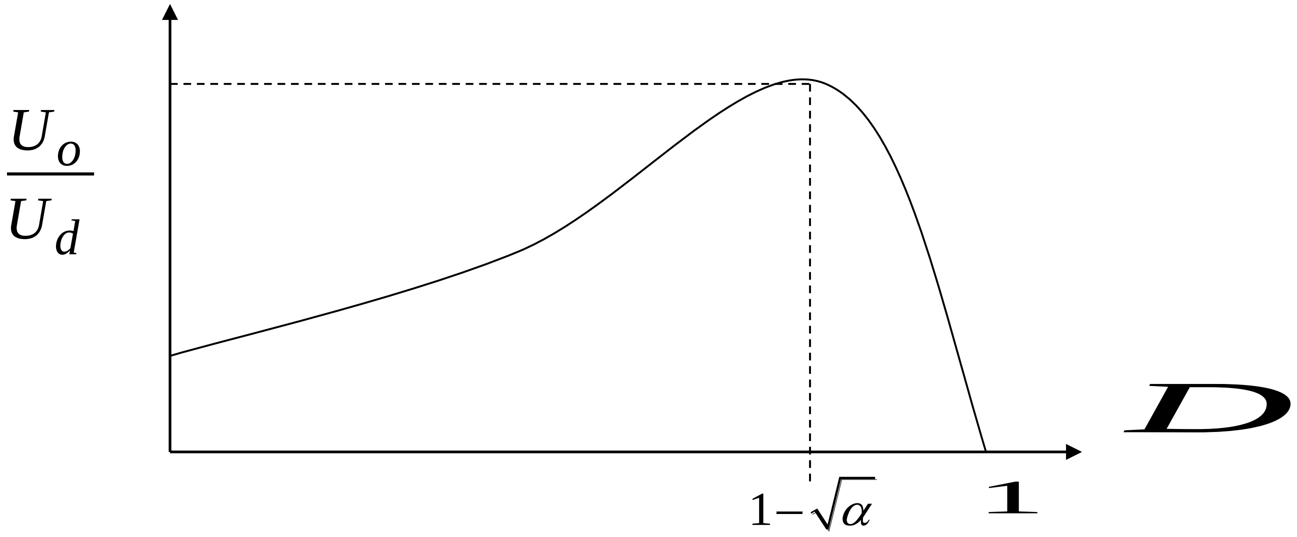
- Up to D ≈ 0,6 ideal and practical curve match well
  - Maximum increase is about 4,7 with 1 % resistors
  - In practice always less than 10, i.e. infinite gain impossible
- E.g. operating at *D* ≈ 0,88
  - Supply voltage reduces
  - Feedback increases *D* in order to increas U_o Because of parasitics U_o actually drops and finally *D* = 1 and short circuit
  - *D* needs to be limited to some practical value

Efficiency with parasitics

- For simplicity parasitics of L considered only

$$R' = r_L + R(1-D)^2$$

$$\frac{U_o}{U_d} = \frac{1-D}{R/r_L + (1-D)^2} = \frac{1-D}{\alpha + (1-D)^2}, \qquad \alpha = \frac{R}{r_L}$$

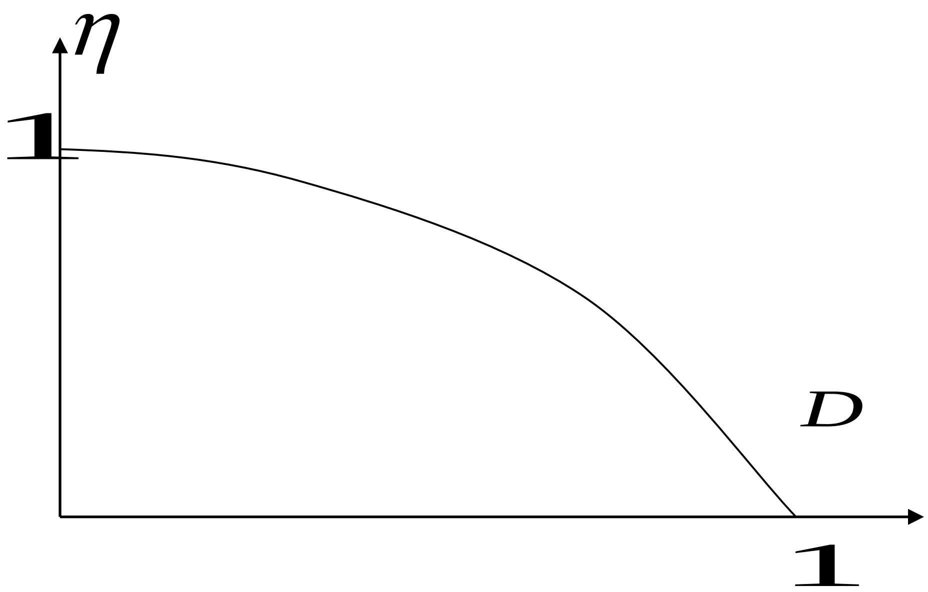


Efficiency with parasitics

- Only inductor losses

$$\eta = \frac{P_o}{P_o + P_{r_L}} = \frac{U_o^2 / R}{U_o^2 / R + I_L^2 r_L} = \frac{1}{1 + \alpha / (1-D)^2}, \qquad \alpha = \frac{R}{r_L}$$

- The higher *D* the smaller efficiency is



Step-Up DC-DC Converter Output Ripple

- ESR is assumed to be zero

•Inductance has no effect as it is in the input side

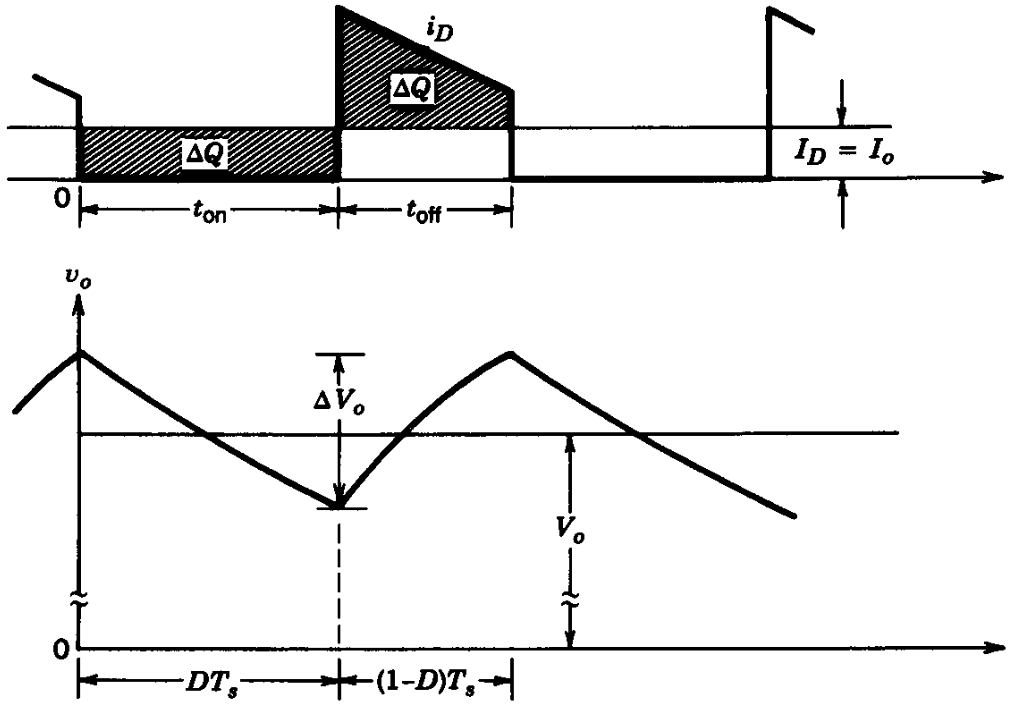
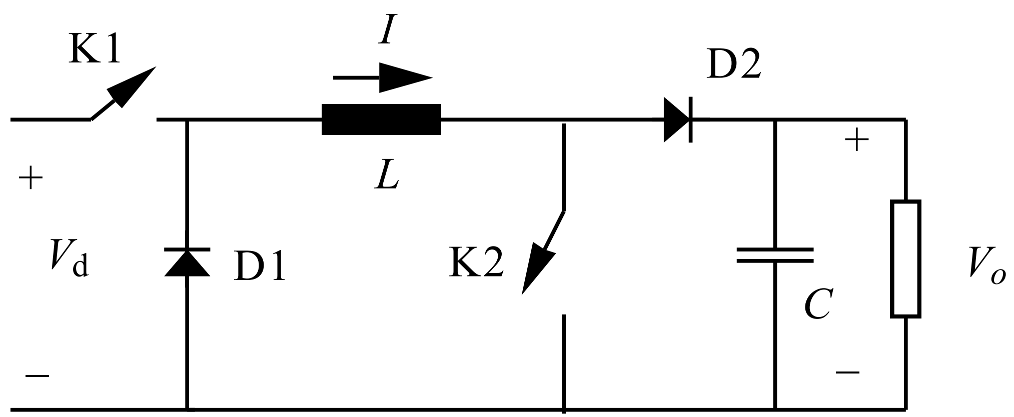


Figure 7-17 Step-up converter output voltage ripple.

$$\Delta U_O = \frac{\Delta Q}{C} = \frac{I_O DT_S}{C} = \frac{U_O}{R}\frac{DT_S}{C} \Rightarrow \frac{\Delta U_O}{U_O} = \frac{DT_S}{RC} = \frac{DT_S}{\tau}$$

Step-Down/Up DC-DC Converter, Buck-Boost

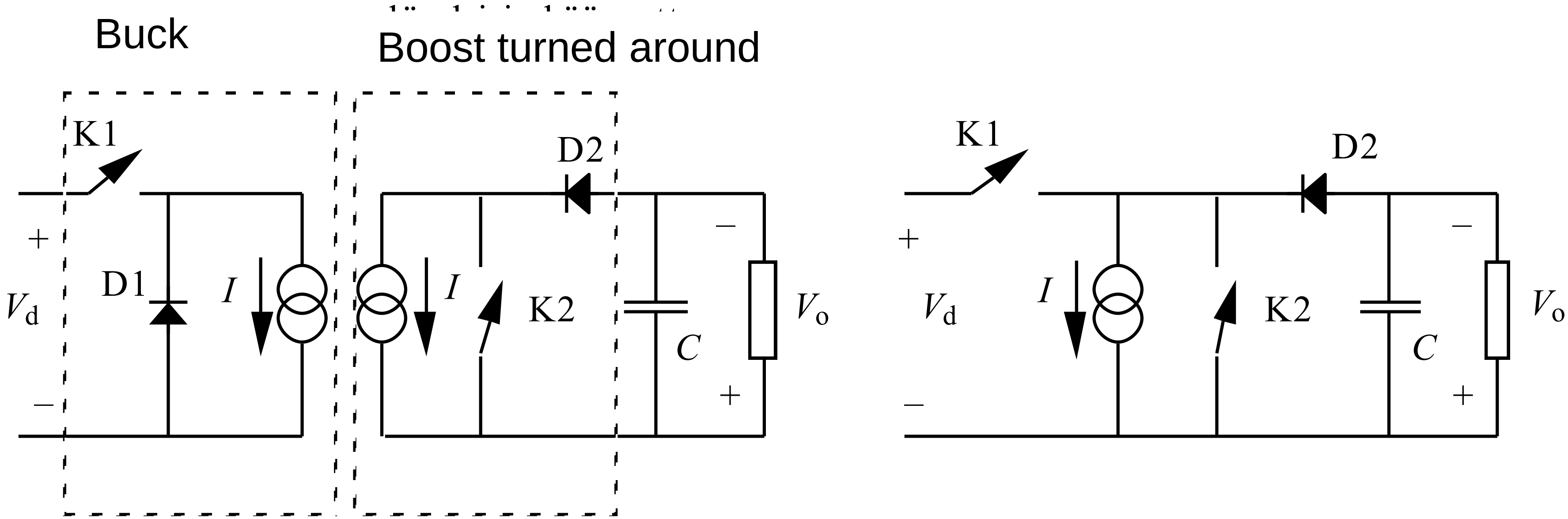
- How to derive Buck-Boost
- Series connection of Buck and Boost



- Buck, K2 is always open
- Boost, K1 is always closed

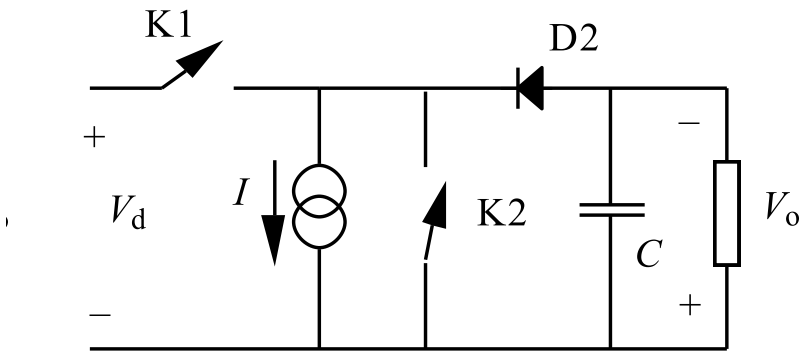
Common current source

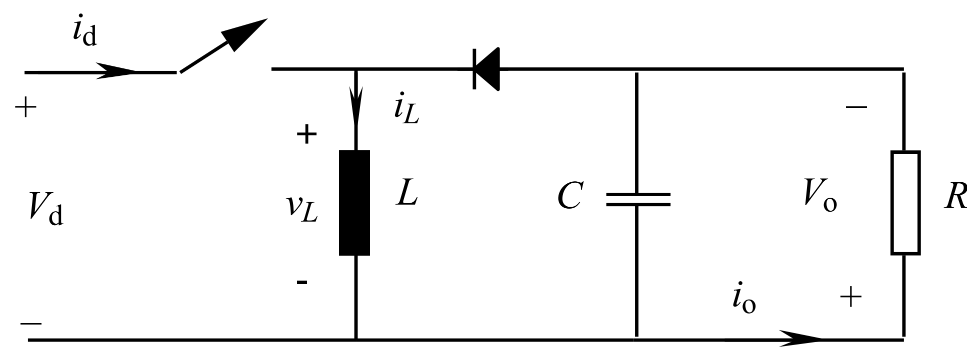
- Same current source, Boost turned around
- D1 needs to be removed, it only short-circuits the current source



Buck-Boost

- K2 can be removed too, it is only short-circuiting current source





Step-Down/Up DC-DC Converter, Buck-Boost

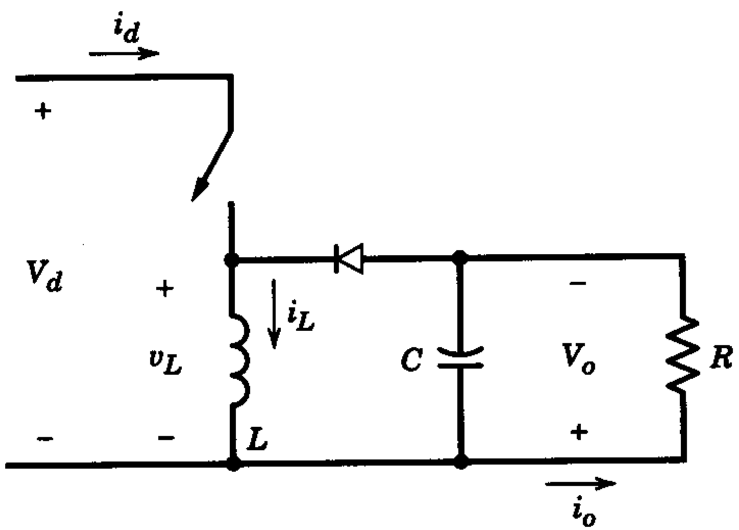


Figure 7-18 Buck–boost converter.

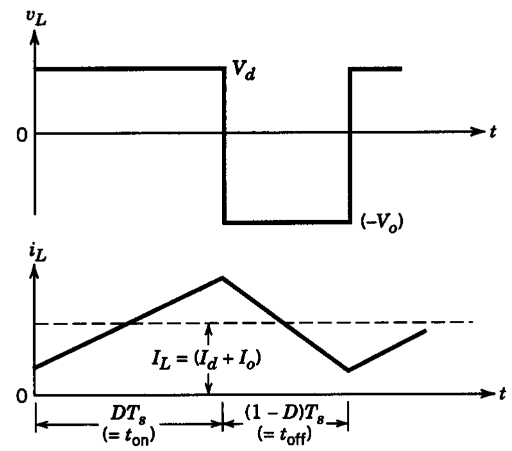
- The output voltage can be higher or lower than the input voltage

Step-Up DC-DC Converter: Waveforms

$$U_d t_{on} - U_o t_{off} = 0$$

$$\Leftrightarrow U_d D T_s - U_o (1-D) T_s = 0$$

$$\Rightarrow \frac{U_o}{U_d} = \frac{D}{1-D} \quad \text{ja} \quad \frac{I_o}{I_d} = \frac{1-D}{D}$$



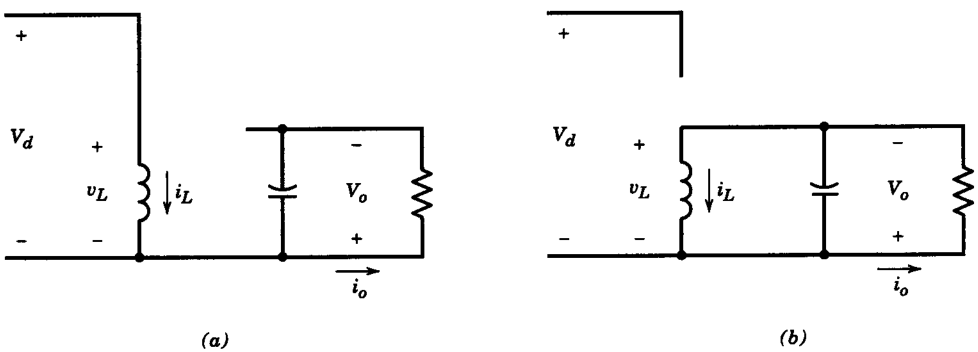


Figure 7-19 Buck–boost converter ($i_L > 0$): (a) switch on; (b) switch off.

- CCM, Continuous conduction mode

Step-Up DC-DC Converter: Limits of Cont./Discont. Conduction, Vo constant

$$I_{LB} = \frac{i_{Lpeak}}{2} = \frac{U_d}{2L} DT_s = \frac{T_s U_o}{2L}(1-D)$$

$$I_o = I_L - I_d \quad \text{ja} \quad I_{oB} = I_{LB} - I_{dB} = (1-D) I_{LB} = \frac{T_s U_o}{2L}(1-D)^2$$

$$I_{oB\max} = \frac{T_s U_o}{2L}$$

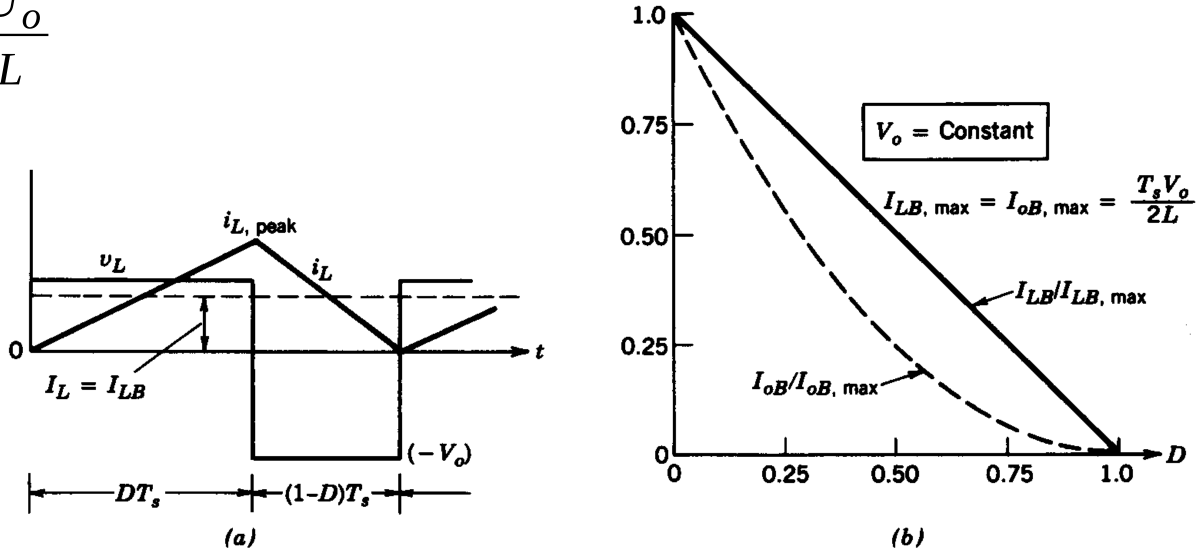


Figure 7-20 Buck–boost converter: boundary of continuous–discontinuous conduction.

Step-Up DC-DC Converter: Discontinuous Conduction Mode, Vo constant

$$U_d D T_s - U_o \Delta_1 T_s = 0 \Leftrightarrow \frac{U_o}{U_d} = \frac{D}{\Delta_1} \text{ ja } \frac{I_o}{I_d} = \frac{\Delta_1}{D}$$

$$I_L = \frac{U_d}{2L} D T_s \frac{D + \Delta_1}{1}$$

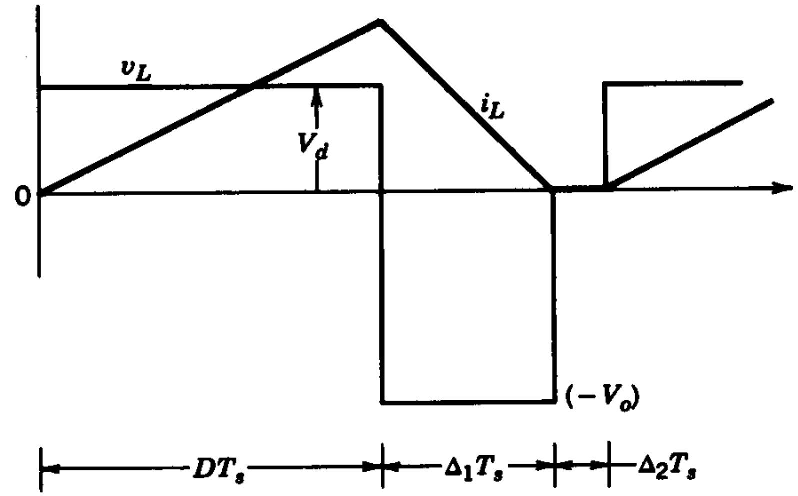


Figure 7-21 Buck–boost converter waveforms in a discontinuous-conduction mode.

$$I_d = I_o = \frac{U_o}{2L} \Delta_1 T_s \frac{\Delta_1 T_s}{T_s} \Rightarrow \Delta_1 = \sqrt{\frac{2L}{U_o T_s} I_o} \text{ eli } D = \frac{U_o}{U_d} \Delta_1 = \frac{U_o}{U_d} \sqrt{\frac{I_o}{I_{oB\max}}}$$

Step-Up DC-DC Converter: Limits of Cont./Discont. Conduction

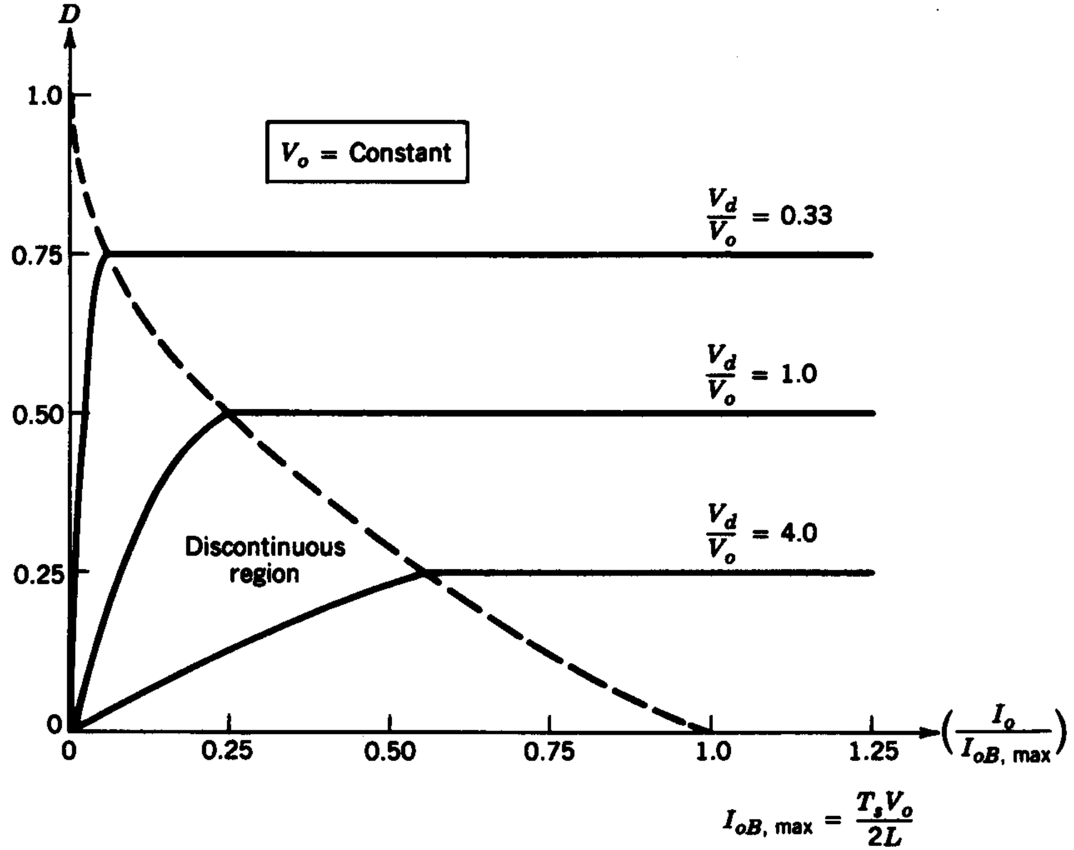


Figure 7-22 Buck–boost converter characteristics keeping V_o constant.

- The output voltage is held constant

Buck-Boost: Effect of Parasitics

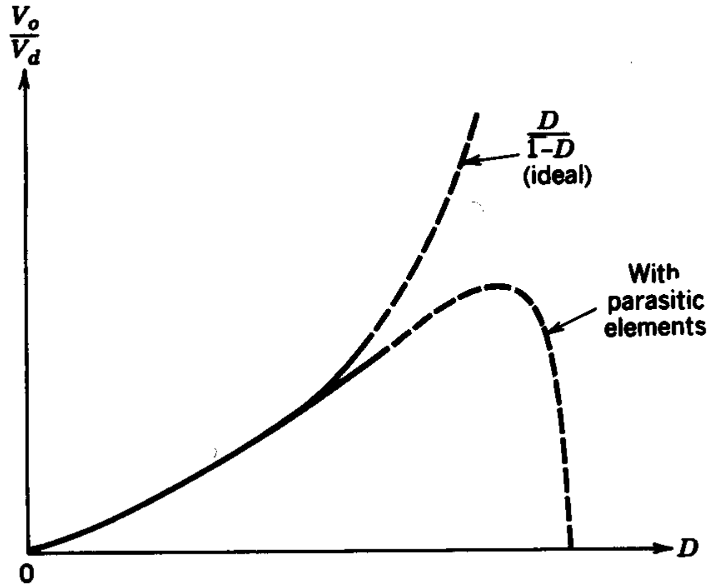


Figure 7-23 Effect of parasitic elements on the voltage conversion ratio in a buck–boost converter.

- The duty ratio is limited to avoid these parasitic effects from becoming significant, same as boost

Step-Up DC-DC Converter: Output Voltage Ripple

- ESR is assumed to be zero
- Inductance not part of ripple equation
- Note $I_L \neq I_o \neq I_o$

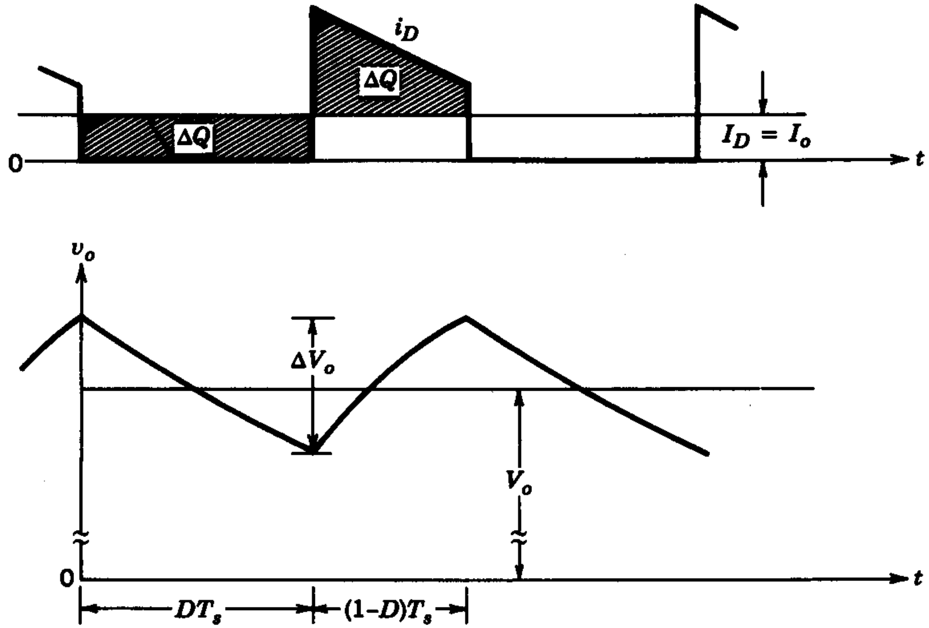


Figure 7-24 Output voltage ripple in a buck–boost converter.

$$\Delta U_o = \frac{\Delta Q}{C} = \frac{I_o DT_s}{C} = \frac{U_o}{R}\frac{DT_s}{C} \Rightarrow \frac{\Delta U_o}{U_o} = \frac{DT_s}{RC} = \frac{DT_s}{\tau}$$

Cuk DC-DC Converter

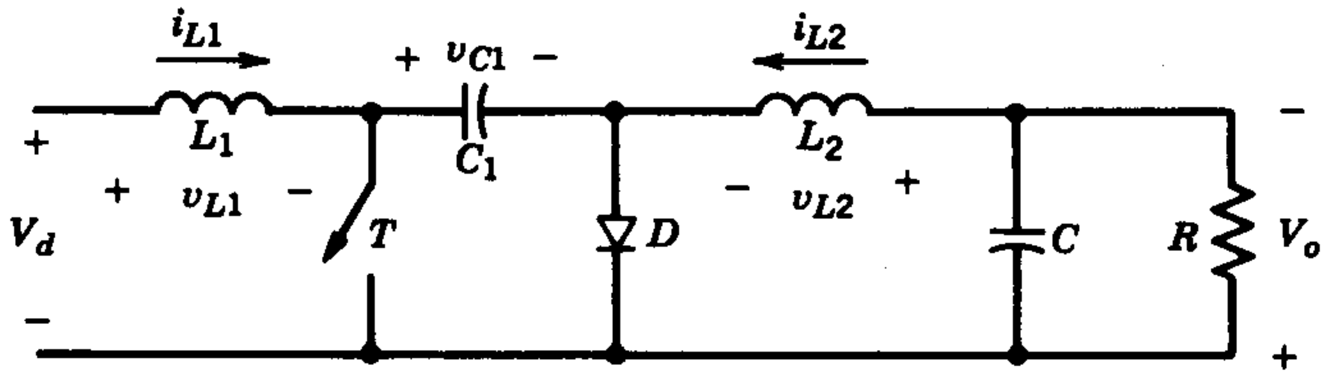


Figure 7-25 Cúk converter.

- Name is based on the family name of the invertor
- The output voltage can be higher or lower than the input voltage, dualism with buck-boost
- Capacitor C1 acts as intermediate energy storage

Cuk DC-DC Converter: Waveforms

- The capacitor voltage is assumed constant

$$U_d D T_s + (U_d - U_{C1})(1-D)T_s = 0 \Rightarrow U_{C1} = \frac{U_d}{1-D}$$

$$(U_{C1} - U_o) D T_s + (-U_o)(1-D)T_s = 0 \Rightarrow U_{C1} = \frac{U_o}{D}$$

$$\frac{U_o}{U_d} = \frac{D}{1-D} \qquad \frac{I_o}{I_d} = \frac{U_d}{U_o} = \frac{1-D}{D}$$

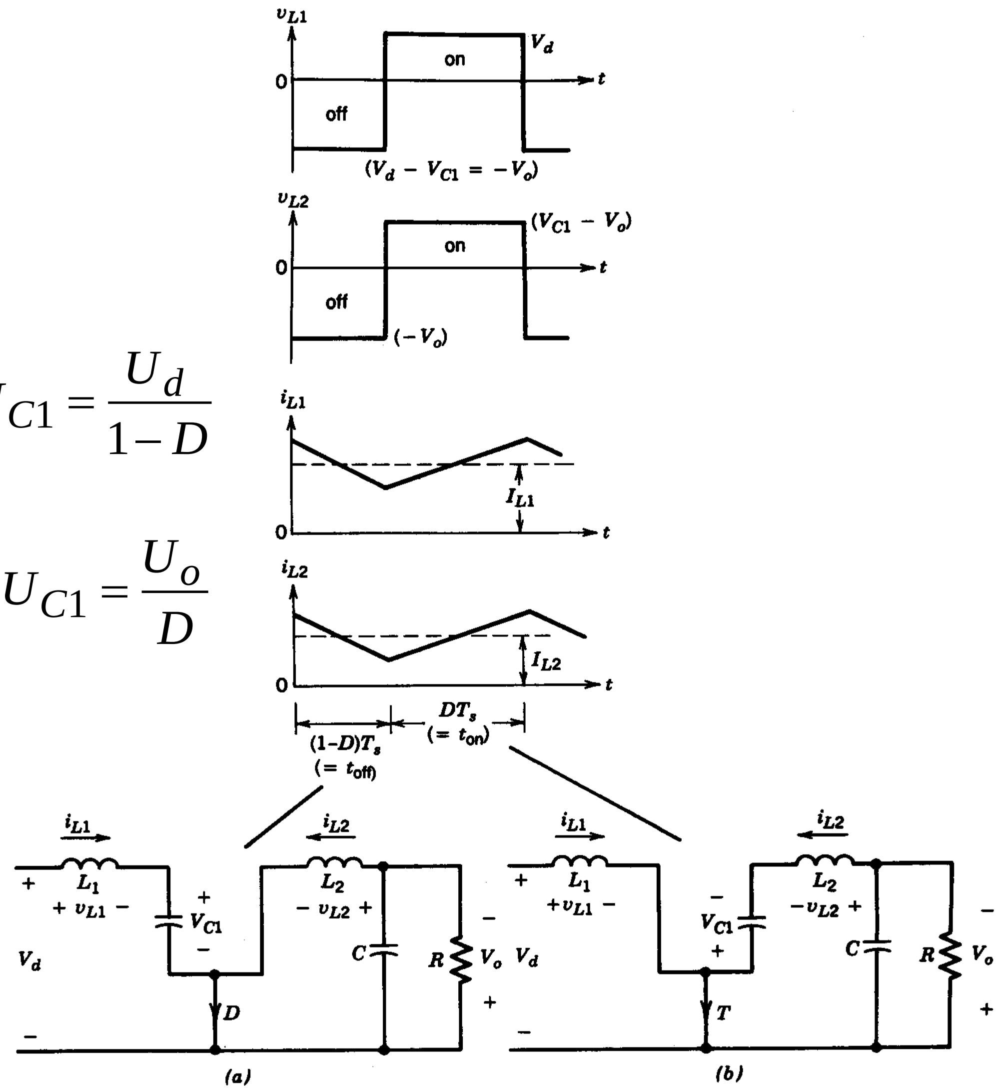
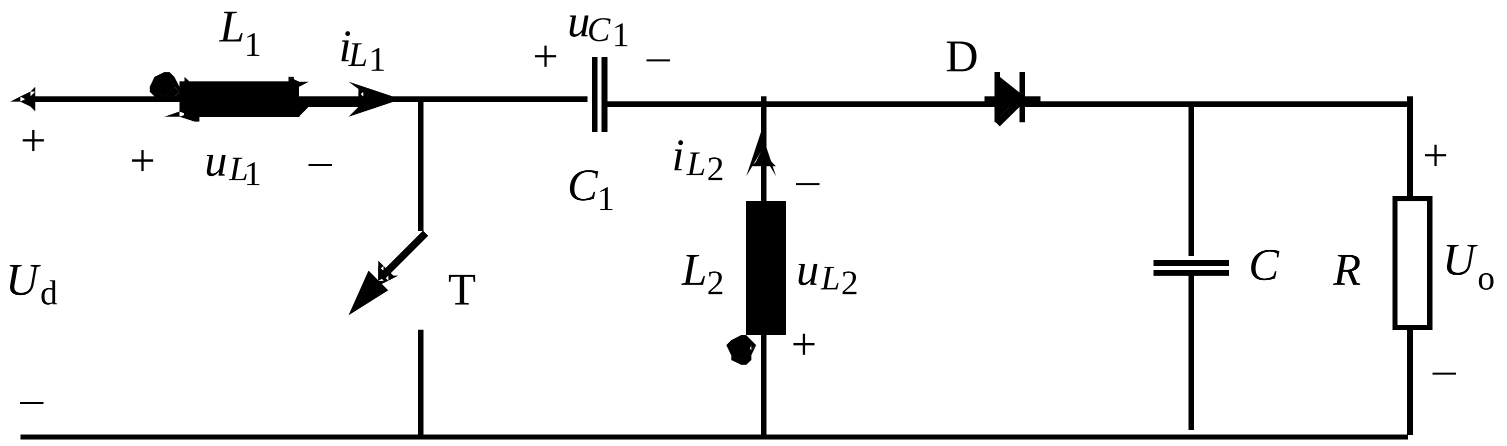


Figure 7-26 Cúk converter waveforms: (a) switch off; (b) switch on.

Sepic Converter

- Single-Ended Primary Inductance Converter
  - L_1:n correspons to Boost
  - L_2:n correspons to Buck-Boost



Sepic comparison

- Advantages
  - Continuous input current as in boost
  - Step up is possible
  - L1 and L2 can be connected magnetically, possible to compensate ripple in one of the inductors
  - Reduces start and short-circuit currents
  - Galvanic isolation by adding a second winding to L2
- Disadvantage
  - Switch and diode current and voltage higher than in Boost

Sepic, voltages

- Similar to Cúk

$$L_1 \qquad U_d D = (1-D)(U_o + U_{C1} - U_d)$$

$$L_2 \qquad U_{C1} D = (1-D) U_o = 0 \Rightarrow U_{C1} = \frac{1-D}{D} U_o$$

$$U_d D = (1-D)\left(U_o + \frac{1-D}{D} U_o - U_d\right) \Rightarrow \frac{U_o}{U_d} = \frac{D}{1-D}$$

Sepic, currents

- In steady state average current of C1 needs to be zero

$i_{C1} = i_{L2}$ Switch conducts

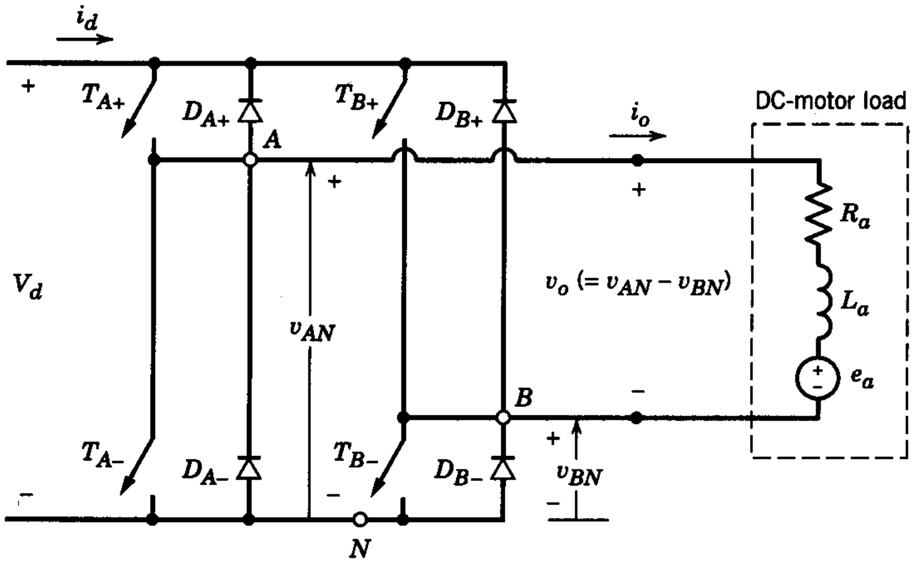
$i_{C1} = i_{L1}$ Switch is not conducting

$$\Rightarrow I_{L2} D = (1-D) I_{L1} = (1-D) I_d \Rightarrow I_{L2} = \frac{1-D}{D} I_d = I_o$$

- $I_{L1} = I_d$ and $I_{L2} = I_o$

Full-bridge dc-dc converter

- Converter for UPS and DC-Motor Drives
  - Either dc or ac output depending on modulation
- Four quadrant operation is possible



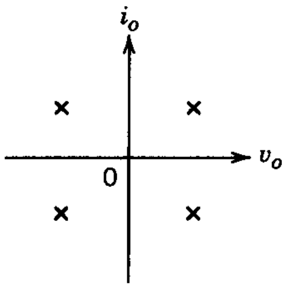


Figure 7-27 Full-bridge dc–dc converter.

Bi-polar voltage switching

- Switches
  - TA+ and TB–
  - TA– and TB+
- Are controlled simultaneously
- Output changes between $+U_d$:n and $–U_d$:n

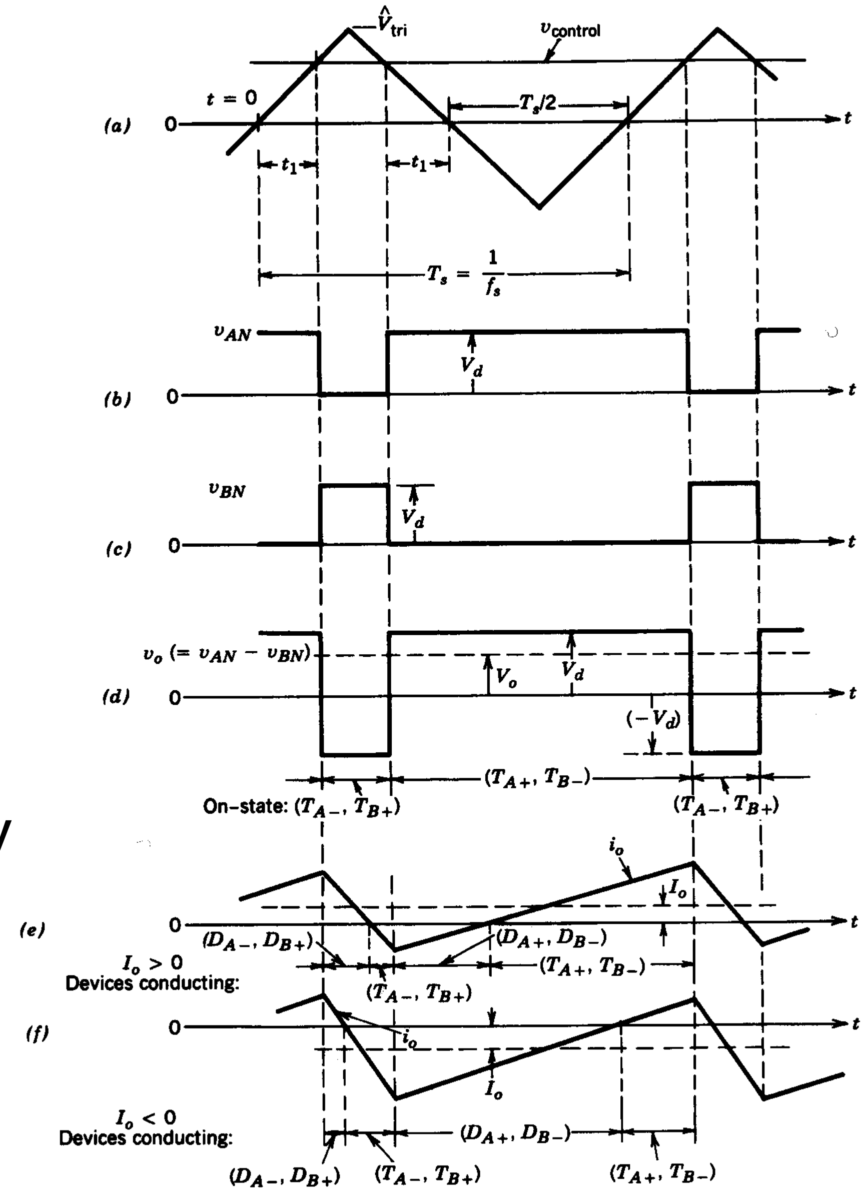


Figure 7-28 PWM with bipolar voltage switching.

Control of output

- Triangle

$$u_{tri} = \hat{U}_{tri} \frac{t}{T_s/4} \quad 0 < t < T_s/4 \qquad t_1 = \frac{u_{control}}{\hat{U}_{tri}} \frac{T_s}{4}$$

- On time of T_{A+} and T_{B-}

$$t_{on} = 2t_1 + \frac{T_s}{2} \qquad D_1 = \frac{t_{on}}{T_s} = \frac{1}{2}\left(1 + \frac{u_{control}}{\hat{U}_{tri}}\right)$$

- On time of T_{A-} and T_{B+}

$$D_2 = 1 - D_1$$

$$U_o = U_{AN} - U_{BN} = (D_1 - D_2)U_d = (2D_1 - 1)U_d$$

$$= \frac{U_d}{\hat{U}_{tri}} u_{control} = \text{Const.} \times u_{control}$$

Uni-polar voltage switching

- Two control voltages with opposite signs

$$D_1 = \frac{t_{on}}{T_s} = \frac{1}{2}\left(1 + \frac{u_{control}}{\hat{U}_{tri}}\right)$$

$$U_o = (2D_1 - 1)U_d = \frac{U_d}{\hat{U}_{tri}} u_{control} = vakio \times u_{control}$$

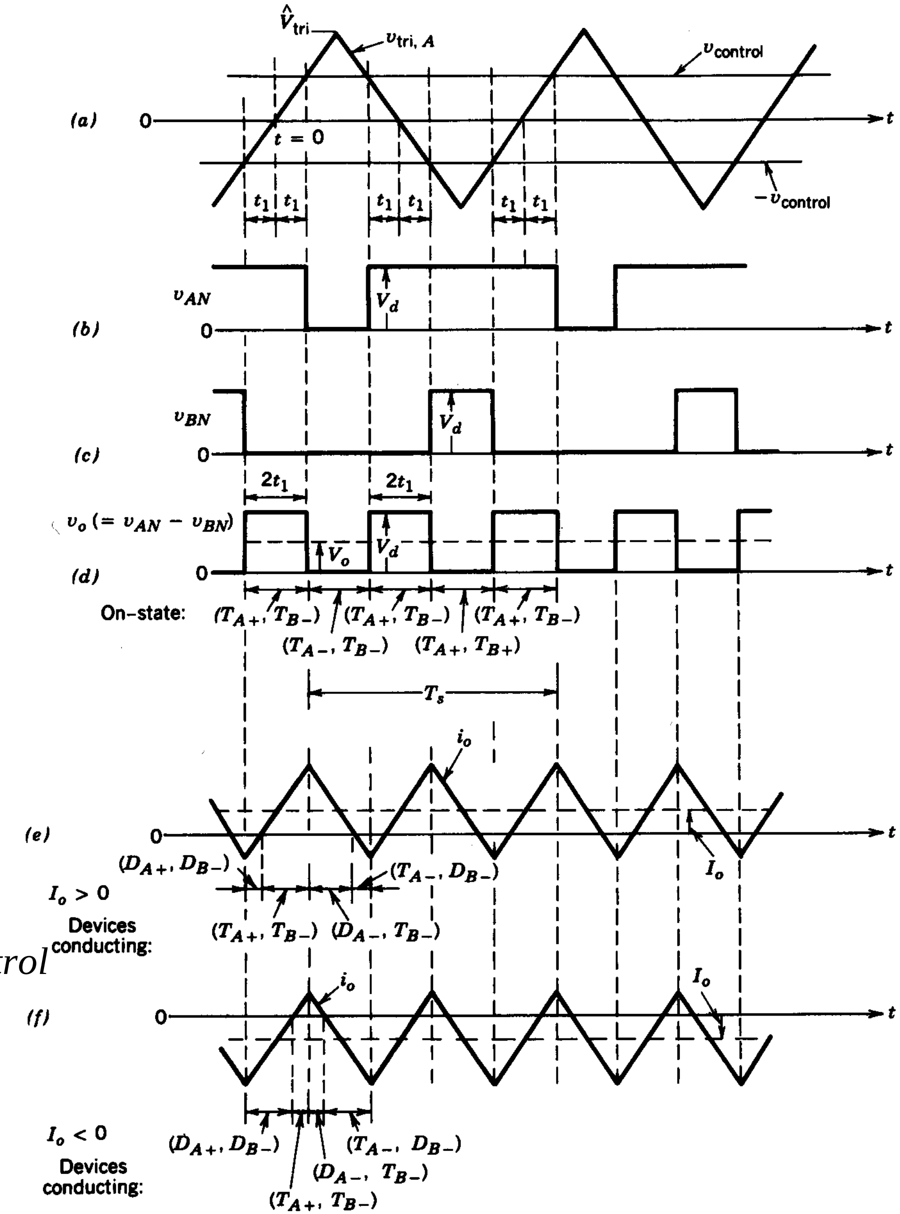


Figure 7-29 PWM with unipolar voltage switching.

RMS of output voltage

- Bipolar

$$U_{o,rms} = \sqrt{\frac{1}{T_s}\int_0^{T_s} u_o^2 dt} = U_d$$

$$U_{r,rms} = \sqrt{U_{o,rms}^2 - U_o^2} = U_d \sqrt{1-\left(2D_1 - 1\right)^2} = 2U_d \sqrt{D_1 - D_1^2}$$

- Unipolar

$$U_{o,rms} = \sqrt{\frac{1}{T_s}\int_0^{T_s} u_o^2 dt} = \sqrt{\frac{4t_1}{T_s}U_d^2} = U_d \sqrt{\frac{u_{control}}{\hat{U}_{tri}}} = U_d \sqrt{2D_1 - 1}$$

$$U_{r,rms} = \sqrt{U_{o,rms}^2 - U_o^2} = U_d \sqrt{\left(2D_1 - 1\right) - \left(2D_1 - 1\right)^2} = U_d \sqrt{6D_1 - 4D_1^2 - 2}$$

Output Ripple in Converters for DC-Motor Drives

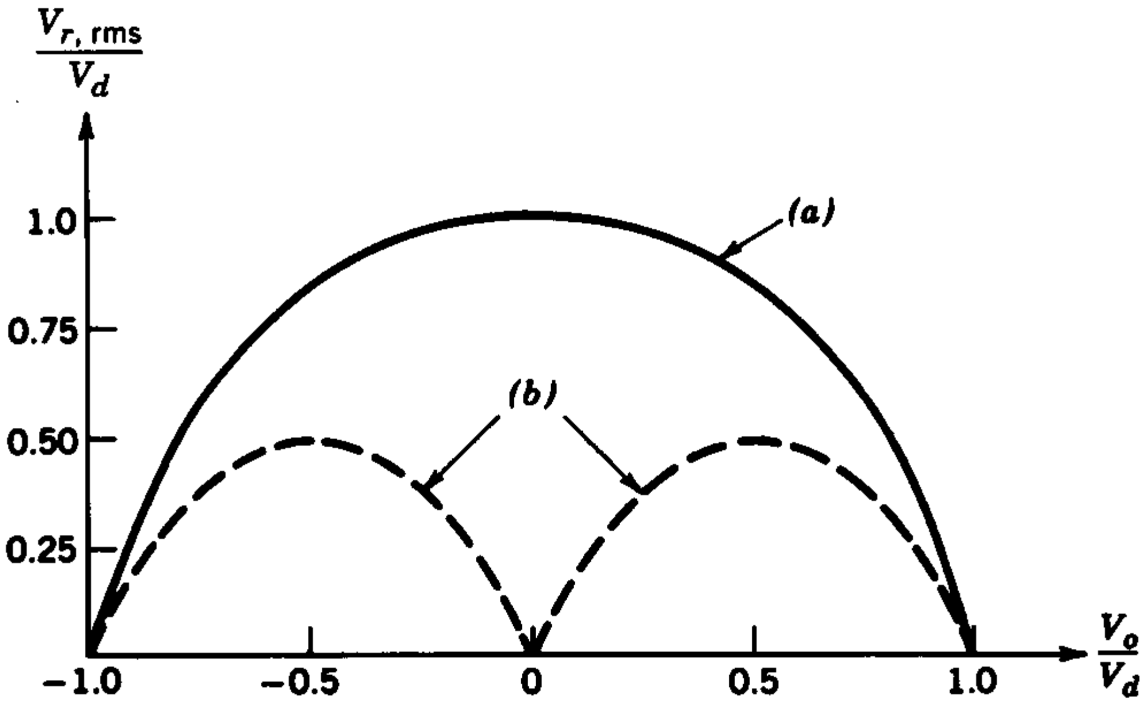


Figure 7-30 $V_{r,\mathrm{rms}}$ in a full-bridge converter using PWM: (*a*) with bipolar voltage switching; (*b*) with unipolar voltage switching.

- bi-polar and uni-polar voltage switching

Switch Utilization in DC-DC Converters

- Ratio
  - U_T = maximum voltage over switch
  - I_T = maximum current

$$\frac{P_o}{P_T} = \frac{U_o I_o}{U_T I_T}$$

- It varies significantly in various converters

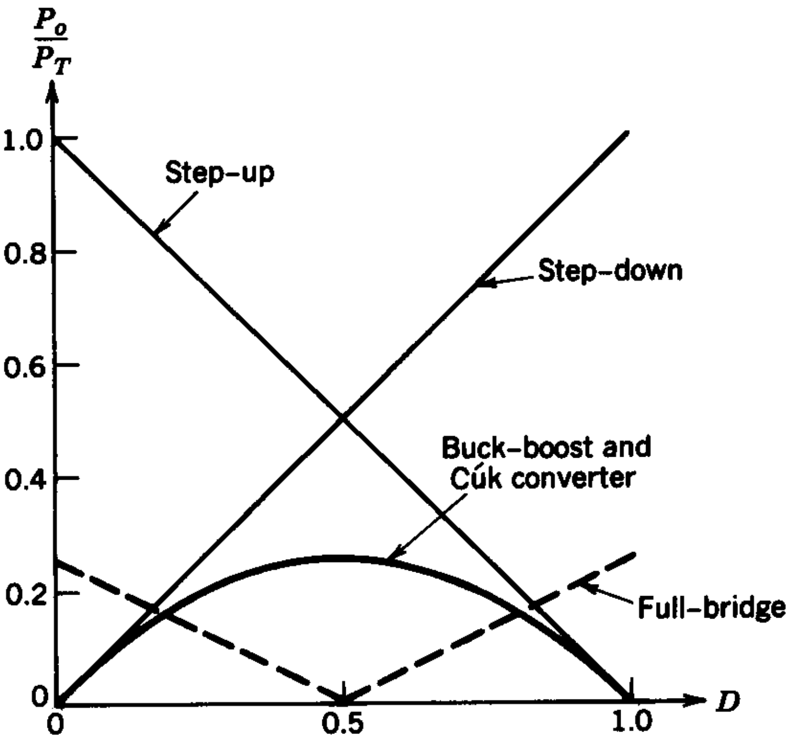


Figure 7-31 Switch utilization in dc–dc converters.

Equivalent Circuits in DC-DC Converters

- replacing inductors and capacitors by current and voltage sources, respectively

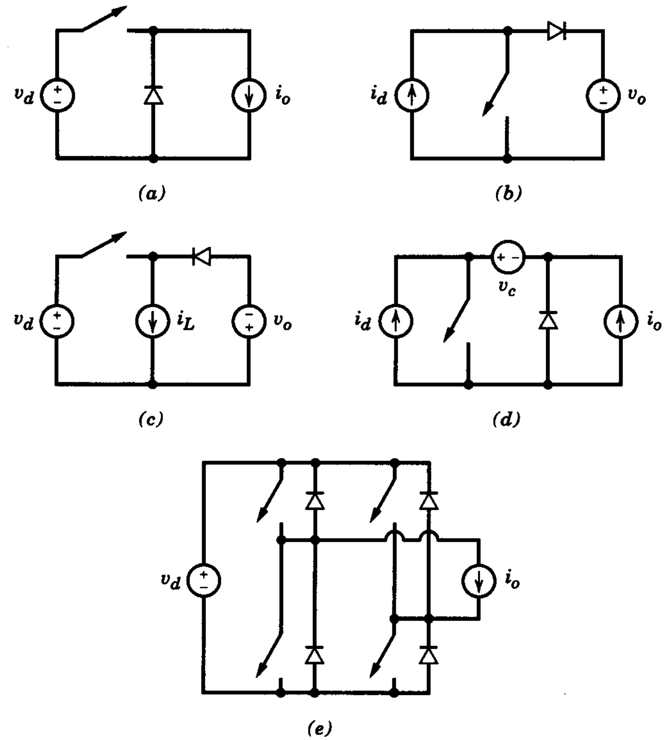


Figure 7-32 Converter equivalent circuits: (*a*) step-down; (*b*) step-up; (*c*) step-down/step-up; (*d*) Cúk; (*e*) full-bridge.

Reversing the Power Flow in DC-DC Conv.

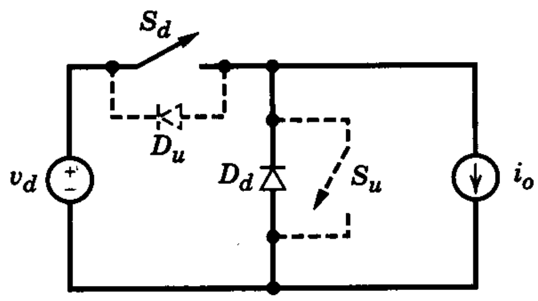


Figure 7-33 Reversible power flow with reversible direction of the output current i_o.

- For power flow from right to left, the input current direction should also reverse

Efficiency and losses of power semiconductor devices

- Losses of power semiconductor devices
  - Conduction losses
  - Switching losses, turn-on and turn-off
- For simplicity following investigation is on Buck converter
  - Can be generalized to other converters

Conduction losses

- On-state voltage drop
  - Assumed to be the same in the switch and diode
- Losses

$$P_{DC} = P_Q + P_D = U_{on} I_o \frac{t_{on}}{T_s} + U_{on} I_o \frac{t_{off}}{T_s} = U_{on} I_o, \quad t_{on} + t_{off} = T_s$$

- Efficiency

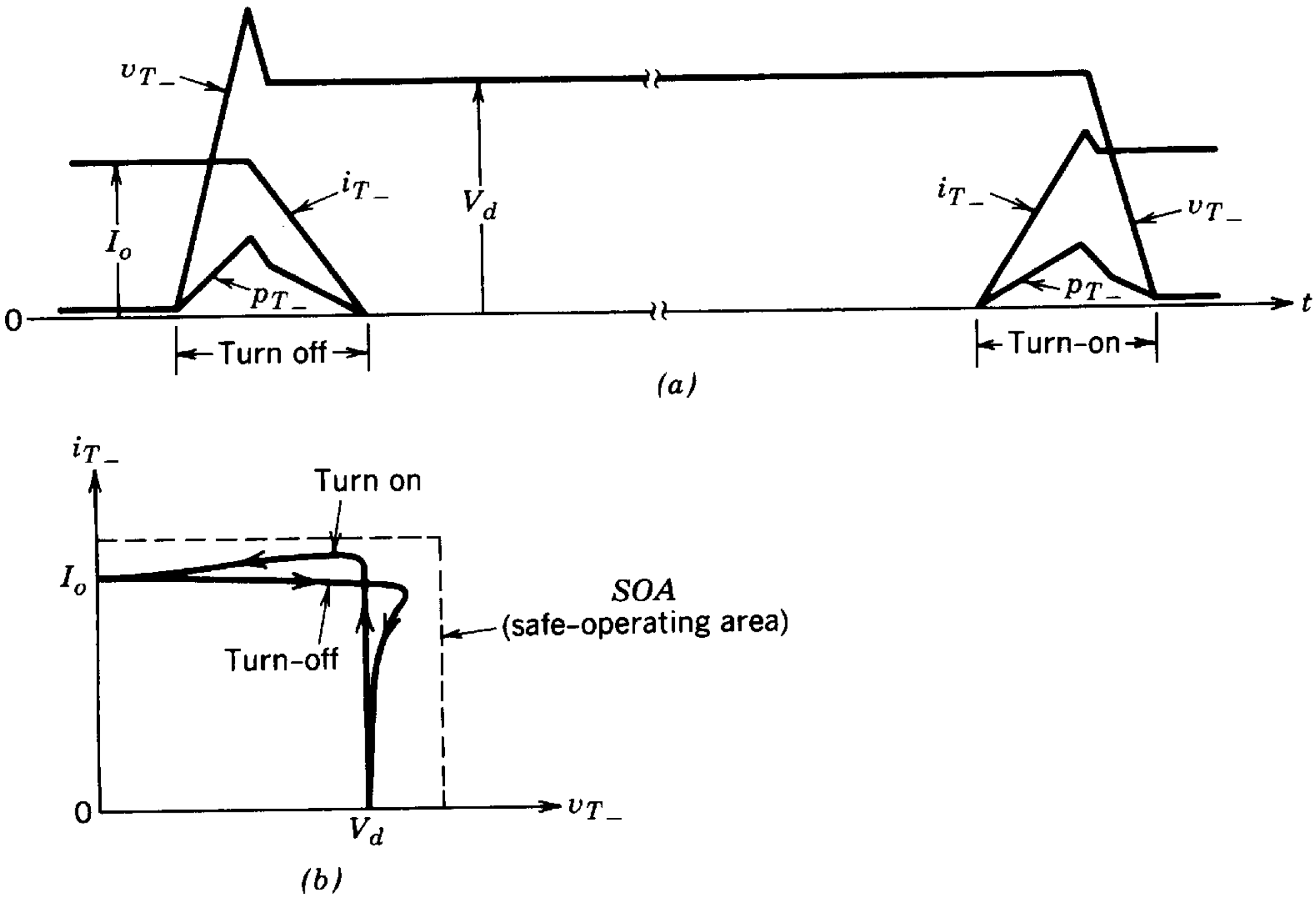
$$\eta = \frac{P_o}{P_o + P_{DC}} = \frac{U_o I_o}{U_o I_o + U_{on} I_o} = \frac{U_o}{U_o + U_{on}}$$

- Example
  - U_o = 3 V, U_{on} = 0,5 V => η = 85,7%

Switching losses

- Infinite rise and fall time when switches are turning on and off
- An ideal switch would
  - Conduct full load current immeadiately without voltage drop
- Current and voltage are assumed to changing linearly during turn-on and -off

Switching inductive current



Turning off and on

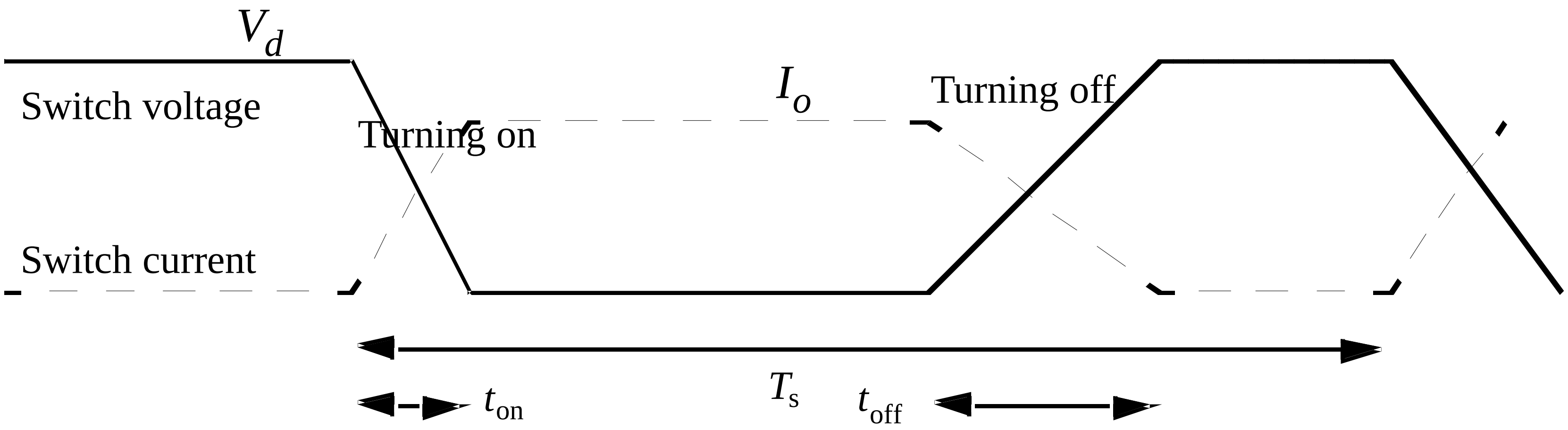
- T- conducts I_o and it is turned off
  - Voltage over it increases and when it is U_d diode D+ starts to conduct
  - Because of parasitic inductances voltage exceeds U_d
- D+ conducts I_o and T- is turned on
  - Current inceares and exceeds I_o because of diode reverse recovery current
  - After recovery of the diode voltage over T- drops to nearly zero

Switching losses, best case

- It is assumed that voltage and current are changing simultaneously

$$P_{on} = \frac{t_{on}}{T_s}\int_0^{t_{on}} uidt = \frac{t_{on}}{T_s}\frac{U_d I_o}{6}$$

$$P_{off} = \frac{t_{off}}{T_s}\int_0^{t_{off}} uidt = \frac{t_{off}}{T_s}\frac{U_d I_o}{6}$$



Conduction and switching losses, best case

- It is assumed that $t_{on} = t_{off}$ $$P_{AC} = P_{on} + P_{off} = \frac{t_{on}}{T_s}\frac{U_d I_o}{3}$$
- Efficiency including conduction and switching losses

$$\eta = \frac{P_o}{P_o + P_{DC} + P_{AC}} = \frac{U_o I_o}{U_o I_o + U_{on} I_o + U_d I_o t_{on}/3T_s} = \frac{U_o}{U_o + U_{on} + U_d t_{on}/3T_s}$$

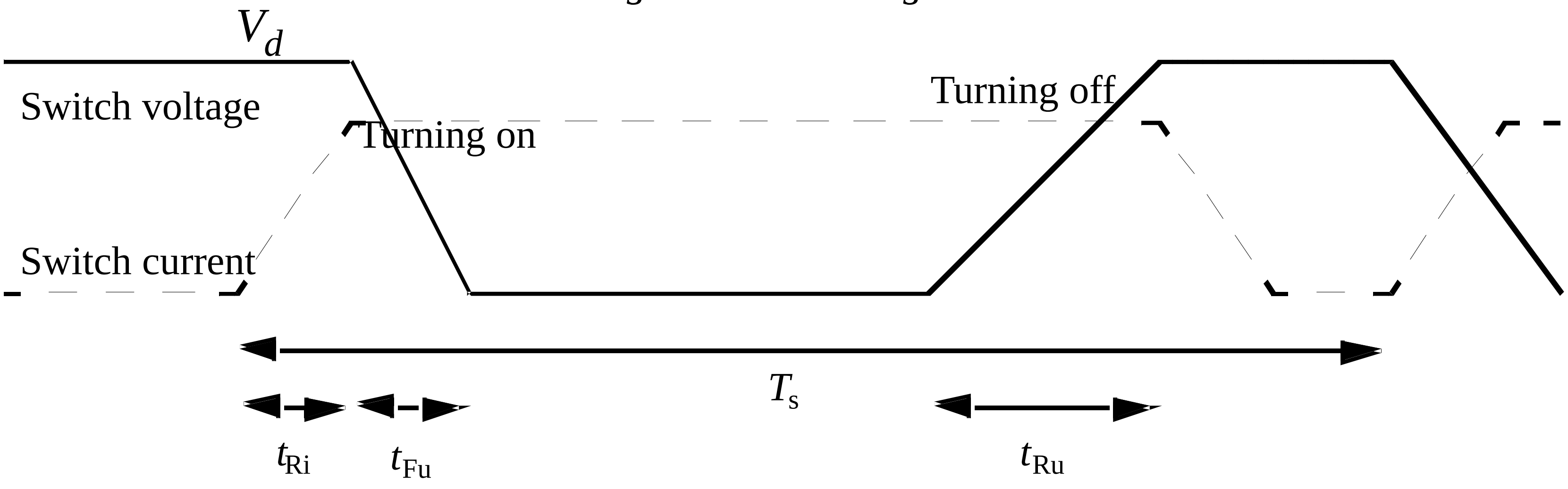
- Example (cont.)
  - Lets assume U_d = 48 V, U_o = 3 V, U_{on} = 0,5 V, f_s = 50 kHz and t_{on} = t_{off} = 0,3 µs and T_s = 20 µs
  - With these numbers $$\eta = \frac{3}{3 + 0,5 + 48 \cdot 0,3/3 \cdot 20} 100\% = 80,2\%$$

Conduction and switching losses, worst case

- Current reaches final value before voltage drops

$$P_{on} = \frac{t_{Ri}}{T_s}\frac{U_d I_o}{2} + \frac{t_{FU}}{T_s}\frac{U_d I_o}{2}$$

$$P_{off} = \frac{t_{RU}}{T_s}\frac{U_d I_o}{2} + \frac{t_{Fi}}{T_s}\frac{U_d I_o}{2}$$



Conduction and switching losses, worst case

- $t_{Ri} = t_{FU} = t_{RU} = t_{Fi}$

$$P_{AC} = P_{on} + P_{off} = 2U_d I_o \frac{t_{Ri}}{T_s}$$

$$\eta = \frac{P_o}{P_o + P_{DC} + P_{AC}} = \frac{U_o}{U_o + U_{on} + 2U_d t_{Ri}/T_s}$$

- Other values same as before, additionally, t_{Ri} = 0,3 µs

$$\eta = \frac{3}{3 + 0,5 + 2 \cdot 48 \cdot 0,3/20} 100\% = 60,7\%$$

- Corresponding linear power supply

$$\eta = \frac{U_o}{U_d} 100\% = \frac{3}{48} 100\% = 6,25\%$$